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&
LIGNARIA
HUNGARICA

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IN FOREST, WOOD
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The Role of Grassy Habitats in Agroforestry

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Abstract – Planting shelterbelts on agricultural fields has long traditions in Hungary. The biodiversity-enhancing effect of this type of agroforestry is intensively researched, but most of the results concentrate on tree species diversity and specific animal communities such as insects and birds. The characteristics of herbaceous vegetation and soil mesofauna related to shelterbelts are understudied; however, both communities play key roles in agricultural productivity. This study aimed to explore the diversity and species composition of these groups in shelterbelts and adjacent grassy and cropped habitats. Samples were taken inside and adjacent to a native and a non-native shelterbelt in an agricultural landscape. The results highlight that shelterbelt edges are at least as important as tree stands in preserving soil-related diversity. Native tree species composition shows slightly more favorable conditions concerning the examined communities. While the positive impact of shelterbelts on the agricultural productivity and the diversity of several animal communities has been proven, the appearance of forest-related herbaceous species in tree stands planted on cultivated fields is not expected, even after decades have passed. The research was supported by the Blue Planet Climate Protection Foundation.

agroforestry / diversity / species composition / herbaceous vegetation / soil mesofauna

Kivonat – A gyepes élőhelyek szerepe az agrár-erdészetben. Magyarországon nagy hagyományokkal rendelkezik a mezőgazdasági területek védelme erdősávokkal. Az agrár-erdészet típusának a biodiverzitást fokozó hatása intenzíven kutatott terület, de az eredmények többsége a fafajok sokféleségére és az állatközösségek szűkebb körére, például rovarokra és madarakra koncentrál. Az erdősávok lágyszárú növényzete és a talajlakó mezofauna jellemzői még kevésbé vizsgált, holott mindkét közösség kulcsszerepet játszik a mezőgazdaság termelés eredményességében. A tanulmány célja ezen csoportok diverzitásának és fajösszetételének feltárása az erdősávokban és a csatlakozó gyepes és kultivált területeken. A mintavételezés mezőgazdasági területre ültetett őshonos és nem honos erdősávokban és környezetükben történt. Az eredmények azt tükrözik, hogy az erdősávok gyepes szegélyei legalább olyan fontosak a talajhoz kötődő diverzitás megőrzésében, mint maga a faállomány. Az őshonos fafajösszetételű erdősáv kissé kedvezőbb képet mutat a vizsgált közösségek szempontjából. Míg az erdősávok pozitív hatása a szántóföldi termesztésre és számos állatközösség diverzitására bizonyított, az erdőhöz kötődő lágyszárú fajok megjelenése még évtizedek után sem várható a mezőgazdasági területekre ültetett faállományokban. A kutatást a Kék Bolygó Klímavédelmi Alapítvány támogatta.

agrár-erdészet / diverzitás / fajösszetétel / lágyszárú növényzet / talajlakó mezofauna

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1 INTRODUCTION

Agroecological systems can provide the opportunity to maintain productivity in a sustainable form (Ball et al. 2018). Agroforestry, a promising aspect of climate change adaptation, integrates woody vegetation into agricultural cultivation, thereby exploiting its various economic, social and ecological benefits. Agroforestry can even revive degraded lands by improving the physical quality of soil once the characteristics of soil aggregate and biological activity are taken into account (Cherubin et al. 2019).

Based on several research results (Feliciano et al. 2018, Jezeer et al. 2019, Elagib – Al-Saidi 2020, Tschora – Cherubini 2020), the advantages of agroforestry can be summarised as follows:

- Soil erosion and runoff control, defending soil from losses of water and nutrients
- Maintaining biological activity, physical properties, and nutrient content of soil for fertility
- Micro-climate regulating
- Providing fodder and shelter for livestock
- Insect pest control
- Eroded and degraded land rehabilitation
- Diversification and stabilisation of farm economy via multiple products
- Promoting nature conservation and biodiversity by providing a framework for above ground and belowground biodiversity

Shelterbelts are the most significant representatives of arable agroforestry in Hungary. While the weed vegetation of intensively cultivated agricultural areas has been widely researched (Pinke – Pál 2005, Pinke et al. 2012, Király – Király 2012, Nagy et al. 2017, Krähmer et al. 2019), research concentrated on shelterbelts has been largely limited to tree species composition and structure surveys (Takács 2008, Jánoska 2012).

According to the technical development of weed management, the number of species adapted to agricultural land use has experienced a significant decline in recent decades (Marshall 2002, Pinke – Pál 2005). Field edges that form a boundary structure with associated habitats can positively affect the weed flora (Marshall – Moonen 2002). These edges offer refuges for many weed species in intensely cultivated environments (Marshall – Arnold 1995).

In appropriate conditions, shelterbelts produce a corridor effect by providing connectivity between woody patches, thereby increasing tree stand area and offering an edge habitat in agricultural landscapes (Damschen 2013). As these corridors increase the number of native plant species, they are an essential tool for biodiversity preservation (Damschen et al. 2006). The presence, absence, or diversity of herbaceous plants can strongly influence the composition and richness of the food chain upon which it is based, and thus the overall biodiversity of the agroforestry system. Therefore, the study of the herbaceous diversity of shelterbelts in agricultural environments is sensible. Acari and Collembola communities play key roles in support productivity under nutrient-poor conditions. Nevertheless, even minor changes in the composition and abundance of these species can significantly affect the local mobilization of nutrients (Heneghan – Bolger 1998). Several studies highlight the role of the food chain and the presence of natural enemies of pests, or even alien, invasive species in agriculture (Schonrogge et al. 1996, Willis – Memmott 2005, Morris et al. 2004). While some weeds can uniquely support the life cycle of a range of insect species, weed diversity strictly correlates with the heterogeneity of plant communities, which affects insectivorous bird communities and other animal communities (Marshall et al. 2003). Also, the presence of seeds is of key importance for granivorous bird species, especially during winter (Buckingham et al. 2011). Many bird species feed primarily on seeds and other parts of plants

as adults, but young individuals need invertebrate food. In addition to the diversity and species composition of vegetation, the density and structure of a plant community are very important for many arthropods that, in turn, provide nutrients for vertebrate animals (Marshall et al. 2003). According to the dispersal of the hedge flora, Marshall (1989) found that the majority of the plants do not spread into the crop field. Some species have limited dispersal into crop areas, and a lower number of species occur as serious field weeds. The field margin, as ecotone, often supports species characteristic to the adjacent habitats and other species that are not present in either adjacent habitats. Thus, a field margin containing grassland, woodland, and ruderal or segetal plants can be more diverse than either the crop field or the woody boundary. Thus, if woody vegetation (trees or shrubs as hedges) border the agricultural fields, the ideal structure of the margin consists of the woody boundary, a nature conservation strip, and the crop edge, which should be completed with a grassy or wildflower margin strip for wildlife or environmental objectives, between the boundary and the crop field. This strip should be free of chemicals (Marshall – Moonen 2002). The aim of the study was to assess the role of shelterbelts and their grassy edges in increasing the soil-related diversity in an intensively managed agricultural area.

2 MATERIALS AND METHODS

2.1 Location of the study area

Surveys were conducted in an intensively managed agricultural landscape in northwest Hungary (Figure 1). Mosonszolnok and its surroundings are typical of the Little Hungarian Plain. An important feature of the sample area is the significant climatic drought, which is caused by the frequent descending westward airflow from the Eastern Alps (Péczeli 1975). In addition, the sediments and alluvium in this area are calcareous, which can increase the effect of climatic drought.



Figure 1. Location of the test site

Sandy muddy loess covers the gravel-based flat alluvial cone (Pécsi 1975). Topsoil depth determines the land use: 40-70 cm deep topsoil is only suitable for poor quality pastures, or where other conditions allow, peach and grape cultivation (Miklay – Molnár 1968). This explains the presence of former pasture fragments on the test site. Agricultural cultivation determines the current appearance of the landscape. The few existing semi-natural habitats are

highly fragmented. A variety of grains are grown on the monocrop fields. Shelterbelts with different tree species compositions provide a poor diversity of the landscape. The shelterbelts here consist of tree stands that are approximately 50 years old and were established primarily for field protection. The current study examined two of these shelterbelts.

Surveys were conducted within the two shelterbelts and in the adjacent habitats: in the grassy edge on both sides of the shelterbelts (EDGE) and in the cultivated fields, 10 m distance from the trees (CULT), with tree repeats (*Figure 2*).

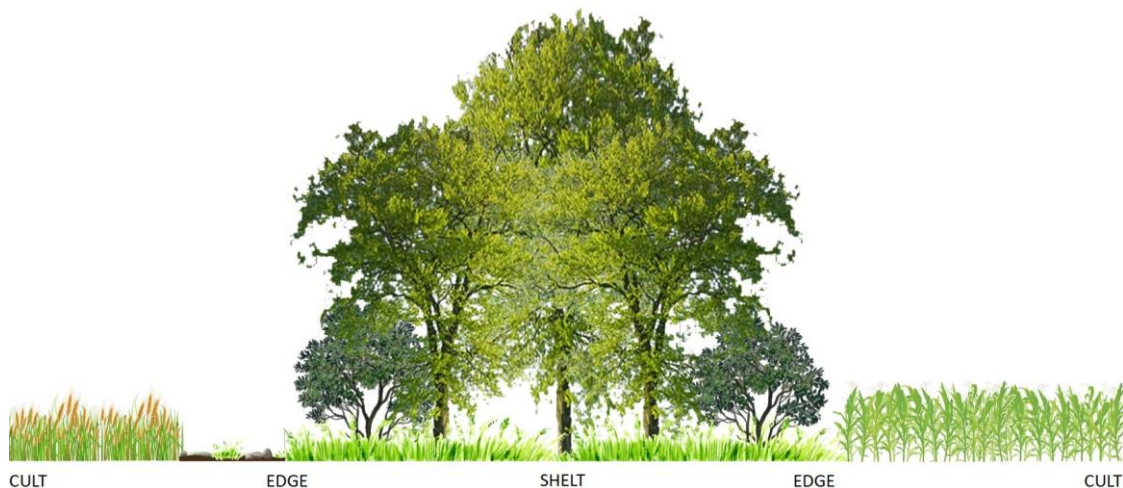


Figure 2. Location of the sampling plots in the shelterbelts and adjacent habitats

2.2 Soil properties

Soil samples were taken from the soil surface (0-10 cm depth) to measure soil parameters. *Table 1* summarises the examined characteristics and the measuring methods.

Table 1. Measured soil parameters and methods

Soil parameter	Measuring method
pH	Ratio of 1:5 soils to distilled water
Soil organic matter content (SOM)	Potassium dichromate capacity method (Búzás 1988)
Available nitrogen ($\text{NO}_3^- + \text{NH}_4^+$)	Parnas-Wagner distillation apparatus (Houba et al. 1986)
Available phosphorus	Ammonium-lactate solution (Hungarian Standard MSZ 20135:1999)
Available potassium	
Particle size distribution	Robinson's pipette method (Pansu – Gautheyrou 2007)
Soil moisture	Gravimetric method, after heating the samples at 105 °C for 24 h (Black 1965)

2.3 Vegetation

Coenological data were collected in 25 m² quadrats with three repeats in all plots (*Figure 2*). Diversity profiles were used to compare the herb layers of the different habitats, calculated with PAST software. PAST uses the exponential of the so-called Renyi index, including the number of species, Shannon diversity, quadratic diversity, and Berger-Parker diversity. The value of the index depends upon the parameter “alpha”. The diversity of the studied communities can be ranked in a partial order with this method (Tóthmérész 2013).

The social behaviour type (SBT) categories are derived from the CSR plant functional system (Grime 1979), adapted to the Pannonian flora by Borhidi (1995). The category of each

plant species was determined based on the role the plant species plays in the communities. The naturalness of the species as well as how it linked to the habitat were also considered. The number and proportion of categories represented in a habitat provide information about the stability, the level of disturbance, or the deviation from the natural state of the community. The specialists (S), competitors (C), generalists (G), and natural pioneers (NP) – with naturalness values of +6, +5, +4, and +3, respectively – are all characteristic to natural habitats. Disturbance tolerants (DT) and weeds (W) appear in disturbed, secondary, and artificial habitats, but still have a positive (2 and 1) naturalness value. Introduced alien species (I), adventives (A), ruderal competitors (RC), and aggressive alien species (AC) represent the most unfavorable categories with negative values: -1, -1, -2 and -3, respectively. The classification of each species was obtained from the Hungarian Flora Database (Horváth et al. 1995). The proportion of species belonging to the different categories in a habitat is displayed with stacked column charts, where the total species number of the examined habitat and the distribution of the species numbers by the SBT categories can be examined simultaneously. (In the case of a small number of species, the SBT categories are not given in the database, which results in a difference between the SBT total number of species and the total number in diversity analysis).

RDA was chosen to analyse the relationship between species composition environmental descriptors observed at the same locations. The species abundance matrix was transformed with the Hellinger method. Hellinger transformation is recommended as a basis for ordination as permits the exploration of the relationships of species to explanatory variables (Legendre – Gallagher 2001). The environmental factors included in the analysis were the impact of measured soil parameters (Table 2), the cover of the different tree species, exposure, and the presence or absence of an earth road separating the examined plot from the cultivated area.

2.4 Soil mesofauna

One hundred cubic centimetres of soil samples were collected with a cylindrical soil core sampler in each coenological quadrat. The microarthropods were extracted with Berlese-Tullgren funnels to 96% ethanol for two weeks. The specimens were classified into major taxonomic groups, while Collembola individuals were determined to the species level. Collembolan diversity was measured with the same method used for herbaceous diversity.

QBS-ar index was employed to evaluate the soil's biological quality (Parisi 2001, Menta et al. 2017). Based on their adaptation to the soil environment, microarthropods are classified into different morphotypes, and characterized with an ecomorphological (EMI) value. The sum of the obtained EMI scores gives the QBS-ar index of the examined sample (Annex IV).

Redundancy analysis was applied to assess the impact of environmental factors on collembolan species composition, with the same method used for herbaceous plants.

3 RESULTS AND DISCUSSION

3.1 Soil habitat condition

The soil parameters (Table 2) show that all of the plots have a neutral to slightly alkaline pH. The texture of the soils is sandy-silty with a low carbonate content. Cultivated plots have the lowest SOM value and, at the same time, the highest phosphorus and potassium content due to fertilization.

3.2 Woody vegetation

The non-native tree stand (ROBINIA) is dominated by black locust (*Robinia pseudoacacia*) and green ash (*Fraxinus pennsylvanica*) in the canopy layer. The shrub layer is poor in species; *Ligustrum vulgare*, *Elaeagnus angustifolia*, and *Maclura pomifera* can be found with low cover. The native shelterbelt (ACER) is composed of native tree species, where field maple (*Acer campestre*), field elm (*Ulmus minor*), Norway maple (*Acer platanoides*) and Turkey oak (*Quercus cerris*) form the canopy layer. The shrub layer is weak, similar to the non-native stand; besides *Ligustrum vulgare*, only *Sambucus nigra* and *Prunus spinosa* appear. The cover values of the canopy and shrub layers in the shelterbelts can be found in Table 3.

Table 2. Measured values of the soil parameters

	Plot	pH (H ₂ O)	CaCO ₃ (%)	SOM	NH ₄ ⁺ + NO ₃ ⁻ N (mg/kg)	AL P (mg P ₂ O ₅ /kg)	AL K (mg K ₂ O/kg)	A%	I%	FH%	DH%	Moist
ROBINIA	CULT	7.76	3.28	0.90	7.10	542.00	614.67	29.33	23.00	43.33	4.33	15.87
	EDGE	7.46	5.51	1.57	8.80	413.67	541.00	27.33	18.00	47.00	7.67	13.73
	SHELT	7.43	3.33	2.10	9.70	125.33	615.67	25.33	23.00	48.00	3.67	13.67
	EDGE	7.42	4.96	1.77	8.43	449.67	523.00	27.67	17.00	48.00	7.33	13.04
	CULT	7.71	2.52	0.87	7.27	561.33	688.00	30.00	22.67	41.67	5.67	14.46
ACER	CULT	7.51	1.63	0.93	6.63	584.67	770.00	31.33	26.33	38.00	4.67	12.13
	EDGE	7.50	7.20	1.67	8.57	314.33	434.00	29.33	19.67	42.33	8.67	11.42
	SHELT	7.51	5.99	1.97	10.07	133.67	513.67	23.33	22.67	43.00	10.67	10.76
	EDGE	7.52	7.08	1.67	8.13	369.67	463.00	29.33	20.33	42.33	8.00	12.70
	CULT	7.49	2.37	0.97	7.17	537.33	735.33	32.00	26.33	36.67	5.00	12.50

Table 3. Cover values of the canopy (A) and shrub (B) layers in the shelterbelts

Layer	Cover (%) of layer		Species	Cover (%) of species	
	ROBINIA	ACER		ROBINIA	ACER
A (10-15 m)	80%	80%	<i>Robinia pseudoacacia</i>	60	
			<i>Fraxinus pennsylvanica</i>	20	
			<i>Acer platanoides</i>	5	
			<i>Maclura pomifera</i>	5	
			<i>Gleditsia triacanthos</i>	5	
			<i>Acer campestre</i>		50
			<i>Ulmus minor</i>		10
			<i>Acer platanoides</i>		10
			<i>Quercus cerris</i>		10
B	40%	20%	<i>Ligustrum vulgare</i>	20	20
			<i>Sambucus nigra</i>		10
			<i>Prunus spinosa</i>		10
			<i>Elaeagnus angustifolia</i>	10	
			<i>Maclura pomifera</i>	5	

3.3 Herbaceous diversity

In total, 50 herbaceous species appeared in the examined quadrats. Only 14 of these were present inside the shelterbelts, while 44 species were found in the grassy edges (Annex II).

In both non-native (ROBINIA) and native (ACER) shelterbelts, the herbaceous diversity of the woody habitat (SHELT) is lower than that of grassy edges (EDGE). Both shelterbelts are very poor in species. This is similar to the results of Carlier – Moran (2019), who found

the herbaceous vegetation of hedgerows very poor in species. The cultivated areas adjacent to ROBINIA were almost totally weed-free in all of the three periods (Figure 3). This may indicate a more intensive weed management activity in the surroundings of this shelterbelt and can explain the lower diversity of the edges and field margins compared to ACER.

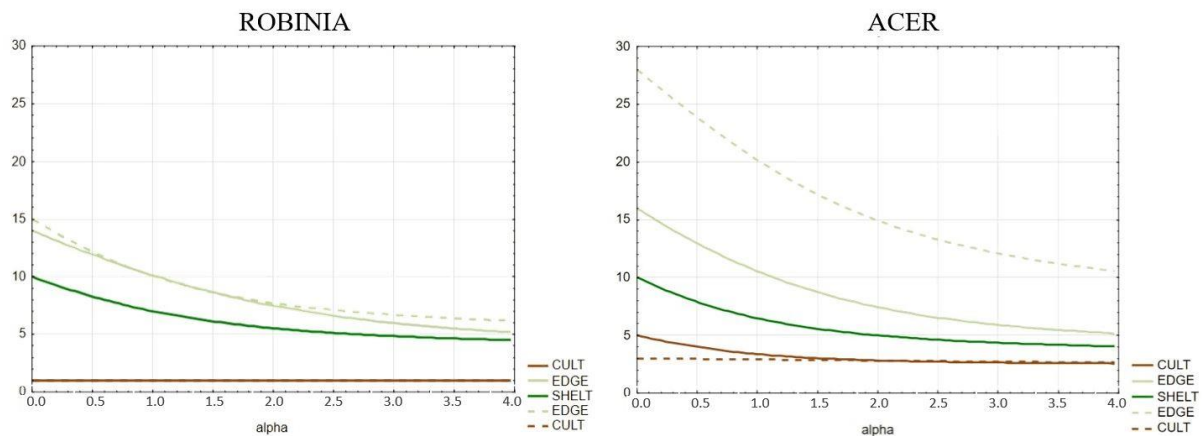


Figure 3. The diversity profiles of the herbaceous vegetation in the shelterbelts and adjacent habitats

The non-woody field margins, grassy edges, and roadside habitats contribute significantly more to the weed diversity of the landscape than shelterbelts do. Romero et al. (2008) also reflected the significance of field margins in enhancing the diversity of the agricultural land, especially in the case of organic farming. Besides increasing weed diversity, Fried et al. (2009) found that field margins act as a refuge for agricultural weed species. A similar phenomenon was experienced at our test site, where numerous segetal weed species were found in the grassy edges, but none of these appeared inside the shelterbelts. Typically forest-related species were not found in the shelterbelts either, which can be explained by the effect of fragmentation and by the fact that most of the forest-related herbaceous species colonise the newly planted woodlands very slowly (Wilson 2019). On the other hand, the agricultural weeds are adapted to open habitats and extensive cultivation (Pinke – Pál 2005). Thus, the conditions in the core of a shelterbelt are not appropriate for these species. This results in lower diversity in the shelterbelts than in the adjacent open habitats.

The herbaceous layer of black locust forests is typically poor in species due to the allelopathic effect of this tree species (Ferus et al. 2019), which causes the homogenization of the plant forest biota (Benesperi et al. 2012). This phenomenon is not evident in the case of the examined shelterbelts. Morrison – Flores (2013) found a significant difference regarding diversity and species composition in the understorey layer for native windbreaks; the appearance of invasive herbaceous species was higher in non-native shelterbelts. This survey was not limited to herbaceous species, but included tree seedlings as well. This method naturally results in a more favourable species construction of the native tree plantations.

3.4 Soil microarthropods

Fifty-five Collembola species were found in the examined soil samples. Four of these appeared only in the native shelterbelts, four in the non-native shelterbelts, and 18 only in non-woody habitats. Six of the species were found only in the grassy edges of the shelterbelts, and three were uncial to cultivated plots (Annex III). According to collembolan diversity, the native shelterbelt (ACER) exhibits slightly better conditions than the non-native belt (ROBINIA). The cultivated plots (CULT) are very poor in species, but the grassy edges of the shelterbelts are quite diverse in most cases (Figure 4).

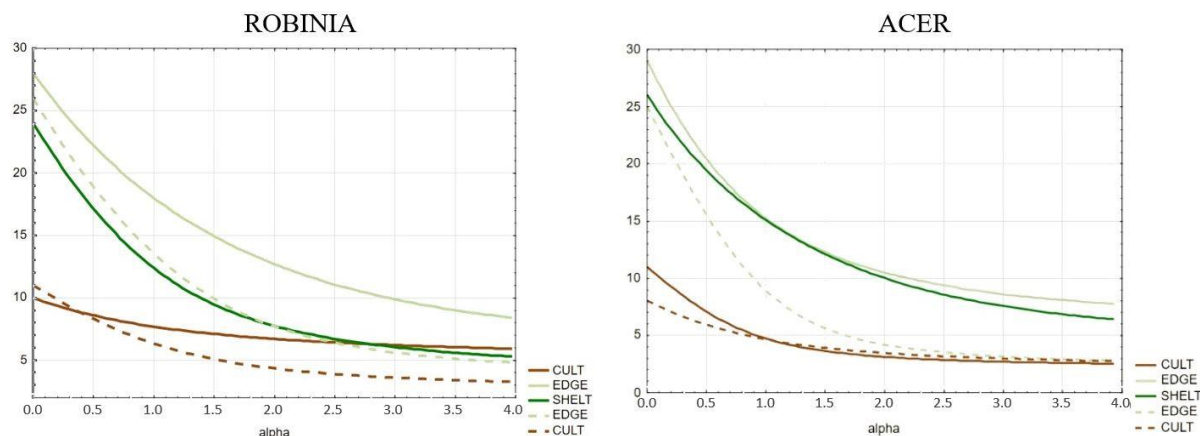


Figure 4. The diversity profiles of springtails (*Collembola*) in the shelterbelts and adjacent habitats

The grassy edges of shelterbelts are at least as favourable a habitat for *Collembola* communities as the core of the shelterbelts are, which is similar to the results of herbaceous diversity examinations. Just a few forest-related *Collembola* species appeared in the soil of the shelterbelts. The reason for this phenomenon is the lack of forest habitats in the landscape and, similar to forest-related herb species, the weak dispersal ability of euedaphic *Collembola* species (Auclerc et al. 2009). The majority of the *Collembola* species are pioneers in both native and non-native shelterbelts, which coincides with the results of Olejniczak (2007). In terms of species richness and diversity, the maple shelterbelt is in a slightly more favourable condition than the black locust stand. Lazzaro et al. (2018) reported that this phenomenon is more significant in forest stands; the study found a remarkable decrease in hemiedaphic and euedaphic microarthropod groups, such as Protura, Acarina, *Collembola*, Diplopoda, Coleoptera, and Thysanoptera in black locust forests, which also can be explained with the allelopathic effect of black locust. Secondary metabolites (e.g., toxalbumins, robin) produced and released by black locust (Hui et al. 2004) often limit the diversity and abundance of microarthropods (Nasiri et al. 2005, Litt et al. 2014). Overall, both shelterbelt types play an essential role in collembolan diversity in agricultural landscapes. Several studies highlight the impact of tree rows in the migration of springtails from woody habitats to cultivated fields (Alvarez et al. 2000, Olejniczak 2007), which positively affects organic degradation and nutrient recycling processes (Menta 2012).

3.5 Qualitative parameters

The majority of the herbaceous plants appearing in the environment of the examined shelterbelts are disturbance tolerant (DT) and weed (W) species, such as *Arrhenatherum elatius*, *Veronica arvensis*, *Lolium perenne*, *Galium aparine*, or *Lamium purpureum*. The specialist (S) and natural competitor (C) categories are totally absent, while ruderal competitors (RC), like *Amaranthus retroflexus*, *Bromus sterilis*, and *Convolvulus arvensis* appear in all examined plots. The cultivated fields are extremely poor in herbaceous species due to weed management. The only generalist appearing in the maple shelterbelt is *Symphytum officinale*, while in the grassy edges, this category is represented by two species: *Poa pratensis* and *Thymus glabra*. Segetal weed species *Consolida regalis*, *Fumaria vaillantii*, and *Viola arvensis* appeared only in the grassy edges.

Regarding microarthropods, 20 taxa were present in the examined soil samples, of which *Collembola* and Acari are the most abundant groups. Both the biological quality of soil (QBS-ar index) and the distribution of herbaceous plant species by social behaviour type (SBT)

categories reveal the importance of shelterbelts and grassy edges in agroforestry as these habitats increase soil-related diversity in the agricultural land (Figure 5).

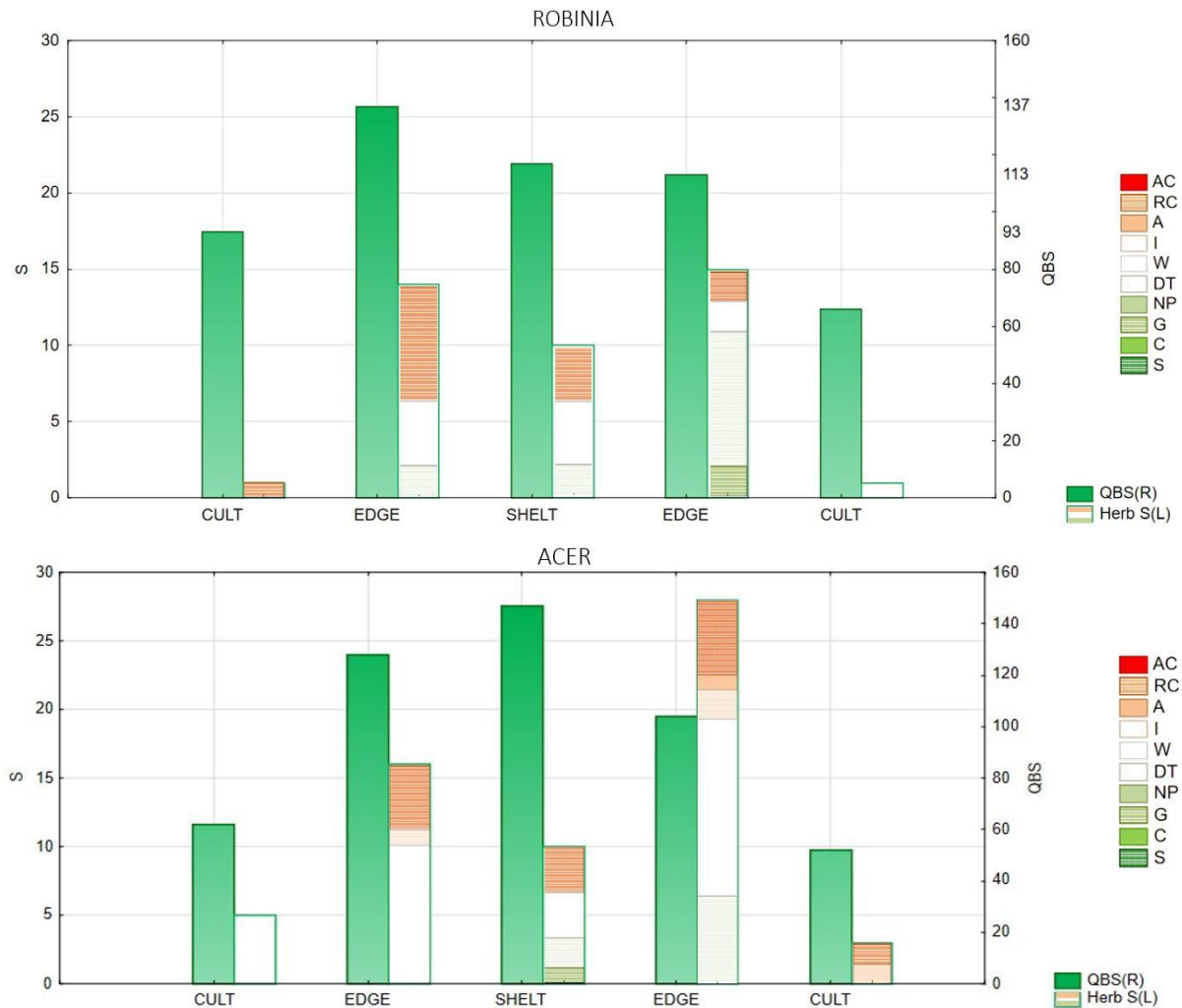


Figure 5. QBS-ar index and the distribution of herbaceous species by SBT categories in the non-native (ROBINIA) and native (ACER) shelterbelts and adjacent habitats

The qualitative traits of herbaceous and microarthropod communities show slightly more favourable conditions in the native shelterbelt. The QBS-ar index of the maple shelterbelt is the highest among the examined plots, while in some cases, this value is higher in the grassy edges than in the black locust belt. The number of ruderal competitor (RC) herbaceous species is similar in the different plots, but the number of native weeds is significantly higher in the edges than it is in the shelterbelts or cultivated fields.

3.6 Species composition

Among soil parameters, CaCO_3 and pH are inversely correlating and determining factors for both communities (Figure 6). However, in the case of vegetation, this relation should be indirect, as the differences in the values are negligible. In practice, this linkage can result from differences in the level of disturbance, which cannot be measured and added to the analysis as a determining factor. The grassy vegetation and the presence of an earth road between the crop field and the edge are also important features. Black locust strongly affects the

collembolan community, contrary to the herbaceous species composition, which is not determined by the tree species primarily.

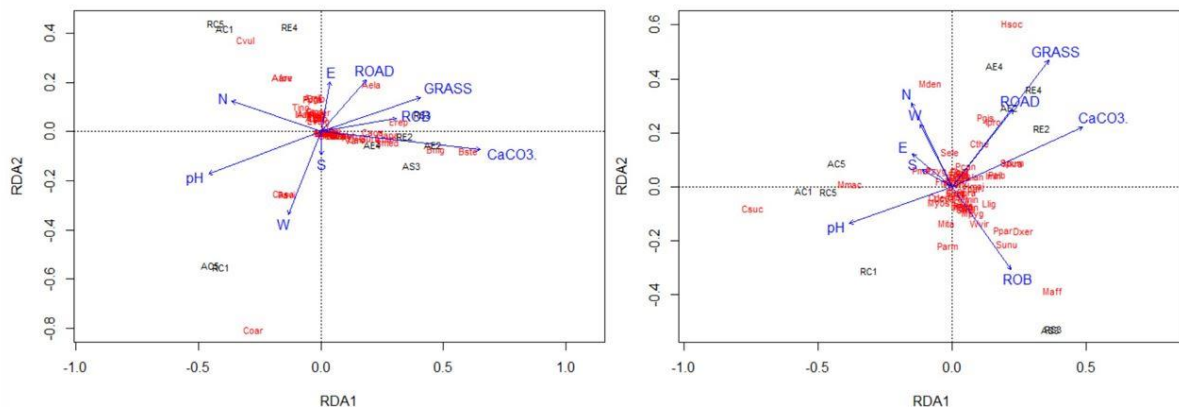


Figure 6. Redundancy analysis of the herbaceous (left) and collembolan (right) communities. Abbreviations: pH: soil pH; CaCO_3 : calcium carbonate content of the soil; N, E, W: northern, western and eastern exposure; ROAD: an earth road separating the shelterbelt edges from crop field; GRASS: the vegetation cover is grass, ROB: the cover value of black locust.

Several studies confirm the positive correlation between herbaceous and Collembola communities (Salamon et al. 2004, Eisenhauer et al. 2011, Perez et al. 2013). The impact of the presence of an earth road between the cultivated field and the edge on the edge flora is confirmed by Sutyinszki et al. (2013), who found that line facilities mitigate the negative effects coming from cultivated fields and, thereby, support the formation of a more diverse edge flora. The sensitivity of Collembola species to herbicides (Frampton et al. 2006) explains that the presence of an earth road determines collembolan species composition. The majority of the herbaceous plants appearing in the environment of the examined shelterbelts are disturbance tolerant (DT) and weed (W) species, such as *Arrhenatherum elatius*, *Veronica arvensis*.

4 CONCLUSIONS

The results showed that the herbaceous flora of shelterbelts planted in agricultural areas is weak, and forest-related herbaceous species do not appear in such tree stands. Despite the allelopathic and nitrogen-fixing effect of black locust, which can lead to habitat transformations, the herbaceous layer is similar to that of the native shelterbelts. The cause of the species-poor herbaceous vegetation in shelterbelts is complex. The main factors are fragmentation, the negative effects of the agricultural surroundings, and the lack of immediate connections to former semi-natural habitats. In addition, the drying climate and the increased game population may contribute to the degradation of the herbaceous flora. The role of non-woody habitats in preserving the agricultural weed flora is higher than that of the shelterbelts. The herbaceous diversity of an agroforestry system can be increased with grassy edges, where a species-rich, even segetal weed community can develop. However, some forest-related Collembola species appeared in the shelterbelts, and the grassy edges are also important habitats for soil mesofauna. The choice of tree species has a greater impact on microarthropods than on herbaceous plants. Overall, chemical-free, extensively mowed grassy strips can contribute significantly to the diversity of the soil-related communities of an agroforestry system.

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APPENDIX*Annex I: GPS coordinates of the sampling plots*

	ROBINIA	ACER
CULT	47.86473, 17.12453	47.86191, 17.19932
	47.86460, 17.12541	47.86250, 17.20066
	47.86444, 17.12718	47.86294, 17.20189
EDGE	47.86485, 17.12455	47.8621, 17.19919
	47.86473, 17.12541	47.86266, 17.20052
	47.86454, 17.12717	47.86313, 17.20165
SHELT	47.86501, 17.12457	47.86219, 17.19912
	47.86484, 17.1254	47.86277, 17.20043
	47.86467, 17.12718	47.86324, 17.20153
EDGE	47.86518, 17.12456	47.86229, 17.19904
	47.86503, 17.12538	47.86286, 17.20031
	47.86484, 17.12721	47.86332, 17.20145
CULT	47.86531, 17.12455	47.86248, 17.19887
	47.86519, 17.12537	47.86304, 17.20019
	47.86496, 17.12722	47.86352, 17.20121

Annex II: Herbaceous species list and cover (%)

Species	SBT	ROBINIA					ACER				
		CULT	EDGE	SHELT	EDGE	CULT	CULT	EDGE	SHELT	EDGE	CULT
Achillea millefolium	DT	0	0	0	20	0	0	0	0	0	0
Allium scorodoprasum subsp. scorodoprasum	DT	0	0	0	3	0	0	0	0	0	0
Amaranthus retroflexus	RC	0	7	0	0	0	0	0	0	5	0
Anagallis arvensis	W	0	0	0	0	0	17	0	0	3	0
Anagallis foemina	W	0	0	0	0	0	17	0	0	3	0
Arrhenatherum elatius	DT	0	13	33	30	0	0	0	0	3	0
Artemisia vulgaris	W	0	0	0	0	0	0	0	0	2	0
Avena fatua	W	0	0	0	0	0	2	0	0	0	0
Ballota nigra	W	0	7	13	0	0	0	27	30	27	0
Bromus sterilis	RC	0	13	33	0	0	0	50	40	17	0
Calamagrostis epigeios	RC	0	3	0	0	0	0	0	0	0	0
Cannabis sativa	A	0	0	0	0	0	0	0	0	3	3
Cardaria draba	W	0	0	0	0	0	0	2	0	8	0
Carduus acanthoides	W	0	7	8	0	0	0	12	0	0	0
Carex hirta	DT	0	0	0	3	0	0	0	0	0	0
Chenopodium album	RC	0	3	0	0	0	0	7	2	2	0
Chenopodium hybridum	W	0	0	0	0	0	0	10	0	7	0
Cirsium arvense	RC	0	3	0	0	0	0	0	0	0	0
Cirsium vulgare	W	0	0	0	0	3	0	0	0	0	0
Consolida regalis	W	0	0	0	0	0	0	0	0	3	0
Convolvulus arvensis	RC	5	7	2	0	0	0	3	7	7	5
Dactylis glomerata	DT	0	0	0	20	0	0	0	0	3	0
Elymus repens	RC	0	40	7	3	0	0	13	0	13	0
Euphorbia peplus	W	0	0	0	0	0	0	0	0	7	0
Falcaria vulgaris	W	0	0	0	0	0	0	2	0	0	0
Fumaria vaillantii	DT	0	0	0	0	0	0	0	0	5	0
Galium aparine	W	0	7	13	0	0	0	10	3	0	0
Geum urbanum	DT	0	0	0	2	0	0	7	17	17	0
Hypericum perforatum	DT	0	0	0	5	0	0	0	0	0	0
Lamium purpureum	W	0	15	5	0	0	0	7	7	0	0
Lathyrus tuberosus	W	0	0	0	0	0	0	0	0	2	0
Linaria vulgaris	W	0	0	0	2	0	0	0	0	0	0
Lolium perenne	DT	0	0	0	7	0	0	0	0	3	0
Medicago sativa	I	0	0	0	0	0	0	0	0	2	0
Mercurialis annua	W	0	0	0	0	0	2	0	0	0	0
Phacelia tanacetifolia	I	0	0	0	0	0	0	2	0	3	0
Plantago lanceolata	DT	0	0	0	5	0	0	0	0	0	0
Plantago major	W	0	0	0	7	0	0	0	0	0	0
Poa pratensis	G	0	0	0	17	0	0	0	0	0	0
Polygonum aviculare		0	0	0	0	0	0	0	0	7	3
Silene latifolia subsp. alba	W	0	0	0	0	0	0	3	0	5	0
Stellaria media		0	2	5	0	0	0	10	10	8	0
Symphytum officinale	G	0	0	0	0	0	0	0	2	0	0
Taraxacum officinale	RC	0	0	0	3	0	0	0	0	0	0
Thymus glabrescens	G	0	0	0	3	0	0	0	0	0	0
Tripleurospermum inodorum	W	0	0	0	0	0	3	0	0	0	0
Urtica dioica	DT	0	0	3	0	0	0	0	0	0	0
Veronica arvensis	DT	0	12	0	0	0	0	0	5	2	0
Veronica persica	W	0	0	0	0	0	0	10	0	3	0
Viola arvensis	W	0	0	0	0	0	0	0	0	2	0

Annex III: Collembola species list

Species	ROBINIA					ACER				
	CULT	EDGE	SHELT	EDGE	CULT	CULT	EDGE	SHELT	EDGE	CULT
Ceratophysella denticulata	0	0	0	0	0	2	0	2	0	0
Ceratophysella luteospina	0	0	7	0	0	0	0	0	0	0
Ceratophysella succinea	14	0	0	0	35	39	0	0	2	11
Hypogastrura socialis	0	54	0	92	4	2	29	0	104	0
Hypogastrura vernalis	0	0	0	0	0	0	3	0	0	0
Schoettella ununguiculata	0	14	47	0	0	0	0	17	0	0
Willemia virae	8	6	14	9	0	0	1	26	6	1
Friezea sp.	0	0	0	0	0	1	2	0	0	0
Deutonura conjuncta	0	0	6	0	0	0	1	2	0	0
Micranurida pygmaea	0	0	3	0	0	0	1	9	0	0
Pseudachorutes parvulus	0	4	28	1	0	0	2	19	0	0
Pseudachorutes pratensis	0	0	8	0	0	0	1	0	1	0
Superodontella lamellifera	0	0	0	0	0	0	0	2	0	0
Protaphorura armata	12	7	38	2	6	3	14	21	3	0
Protaphorura campata	0	0	12	0	0	0	0	0	0	0
Protaphorura cancellata	0	3	0	0	0	0	4	0	1	0
Protaphorura gisini	0	18	0	10	0	1	22	0	9	0
Doutnacia xerophyla	0	1	67	12	0	0	5	23	1	0
Mesaphorura critica	11	16	2	12	2	0	4	0	3	0
Mesaphorura italica	4	0	0	0	0	0	0	7	0	0
Mesaphorura krausbaueri	0	9	14	19	0	0	15	4	3	0
Mesaphorura macrochaeta	0	0	0	0	5	22	0	0	0	4
Mesaphorura yosii	3	0	0	0	0	0	0	0	0	0
Metaphorura affinis	0	11	126	9	0	0	0	87	0	0
Metaphorura denisi	0	12	5	39	2	3	52	0	21	26
Cryptopygus bipunctatus	0	0	0	0	0	0	0	12	0	0
Cryptopygus thermophilus	0	7	0	3	0	0	4	0	7	0
Folsomia manolachei	0	0	9	0	0	0	0	0	0	0
Folsomides parvulus	0	2	12	4	7	0	7	7	3	0
Isotomodes productus	0	11	0	14	0	0	14	0	8	0
Proisotoma minuta	0	0	0	0	0	0	0	8	0	0
Isotoma caerulea	0	2	0	0	0	0	2	0	0	0
Isotoma viridis	0	0	0	9	0	0	0	0	0	0
Parisotoma notabilis	7	17	12	11	19	3	53	27	21	9
Isotomiella minor	0	28	9	7	0	0	0	0	0	0
Entomobrya corticalis	0	0	1	0	0	0	0	0	0	0
Entomobrya multifasciata	0	4	0	6	0	0	0	2	0	2
Entomobrya quinquelineata	0	0	0	2	0	0	0	0	1	0
Orchesella cincta	1	3	4	1	3	0	1	2	3	0
Lepidocyrtus cyaneus	3	2	0	0	0	0	0	0	0	0
Lepidocyrtus lanuginosus	0	0	0	0	0	0	12	7	4	0
Lepidocyrtus cf. lignorum	0	0	6	0	0	0	7	19	5	0
Lepidocyrtus paradoxus	0	0	0	1	0	0	0	0	0	0
Heteromurus major	0	0	5	0	0	0	3	2	5	0
Tomocerus juv	0	0	0	0	0	0	0	1	0	0
Pseudosinella alba	0	18	13	8	0	2	11	8	3	0
Pseudosinella octopunctata	1	2	0	5	0	0	0	0	2	0
Pseudosinella petterseni	0	4	0	0	0	0	0	1	0	1
Pseudosinella zygophora	0	0	3	2	3	0	1	0	3	2
Cyphoderus albinus	0	1	0	3	0	0	0	0	0	0
Megalothorax minimus	0	0	0	0	0	0	4	9	0	0
Bourletiella arvalis	0	2	0	0	0	0	0	0	0	0
Sphaeridia pumilis	0	9	0	14	0	0	17	28	4	0
Sminthurinus elegans	0	7	0	6	1	2	2	0	2	0

Annex IV: calculation of QBS-ar index

Microarthropod taxa individuals	ROBINIA				ACER					
	CULT	EDGE	SHELT	EDGE	CULT	CULT	EDGE	SHELT	EDGE	CULT
ACARI	276	823	1128	530	214	329	643	1236	571	179
ARANEAE	1	3	2	1	0	0	3	4	2	0
CHILOPODA	0	1	2	0	0	0	0	1	0	0
COLEOPTERA	3	3	3	1	0	1	5	5	2	1
COLEOPTERA larvae	3	11	9	8	0	1	3	14	4	1
COLLEMBOLA	64	274	451	301	87	80	294	352	225	56
DIPLOPODA	0	2	0	0	0	0	0	1	0	0
DIPLURA	2	6	5	9	5	0	7	7	4	0
DIPTERA LARVAE	0	0	2	2	0	1	1	0	3	0
HEMIPTERA	0	0	0	1	0	0	0	0	2	0
HYMENOPTERA - ANTS	0	12	2	6	5	0	6	0	17	0
LARVA HYMENOPTERA	0	0	0	2	0	0	0	0	0	0
ISOPODA	0	0	0	0	0	0	0	0	0	0
LARVA LEPIDOPTERA	0	0	0	0	0	0	1	0	0	0
PAUROPODA	1	2	0	0	0	0	0	0	0	0
PROTURA	0	0	0	0	0	0	2	4	0	0
PSEUDOSCORPIONIDA	0	0	0	0	0	0	0	3	0	0
PSOCOPTERA	16	5	7	0	8	4	2	0	9	7
SYMPHYLA	0	5	3	2	0	0	6	7	2	0
THYSANOPTERA	0	2	7	2	0	0	1	3	4	0

Microarthropod taxa EMI scores	ROBINIA				ACER					
	CULT	EDGE	SHELT	EDGE	CULT	CULT	EDGE	SHELT	EDGE	CULT
ACARI	20	20	20	20	20	20	20	20	20	20
ARANEAE	1	5	5	1	0	0	5	1	5	0
CHILOPODA	0	10	10	0	0	0	0	10	0	0
COLEOPTERA	1	5	5	5	0	1	5	5	1	1
COLEOPTERA larvae	10	10	10	10	0	10	10	10	10	10
COLLEMBOLA	20	20	20	20	20	20	20	20	20	20
DIPLOPODA	0	10	0	0	0	0	0	10	0	0
DIPLURA	20	20	20	20	20	0	20	20	20	0
DIPTERA LARVAE	0	0	10	10	0	10	10	0	10	0
HEMIPTERA	0	0	0	1	0	0	0	0	1	0
HYMENOPTERA - ANTS	0	5	5	5	5	0	5	0	5	0
LARVA HYMENOPTERA	0	0	0	10	0	0	0	0	0	0
ISOPODA	0	0	0	0	0	0	0	0	0	0
LARVA LEPIDOPTERA	0	0	0	0	0	0	1	0	0	0
PAUROPODA	20	20	0	0	0	0	0	0	0	0
PROTURA	0	0	0	0	0	0	20	20	0	0
PSEUDOSCORPIONIDA	0	0	0	0	0	0	0	20	0	0
PSOCOPTERA	1	1	1	0	1	1	1	0	1	1
SYMPHYLA	0	10	10	10	0	0	10	10	10	0
THYSANOPTERA	0	1	1	1	0	0	1	1	1	0
QBS-ar	93	137	117	113	66	62	128	147	104	52

Correspondence Between Vegetation Patterns and Soils in Wet and Wet-mesic Grasslands of Hanság and Tóköz (Hungary)

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Abstract – Our research focused on the causes responsible for the fine mosaic pattern of plant associations on wet and wet-mesic meadows. The study area is located in the Little Hungarian Plain, including the former swamp basins of Hanság and Tóköz in Hungary. The vegetation survey data were evaluated by statistical methods (TWINSPAN method), and vegetation maps of the areas were prepared. Topsoil samples near the relevés were gathered for further laboratory tests. Soil profiles were opened by a Pürckhauer soil sampler for on-site description of the soil horizons and classification. Surface models provided a base for the preparation of contour maps that could be compared with the vegetation pattern. We found that of the two dominant vegetation types, mesotrophic wet meadows were associated with Mollic Gleysols, while non-tussock sedge beds were associated with Histic Gleysols. At the transitions of the two soil classes, the subgroup of non-tussock sedge beds is the dominant type. The soil class only determined the plant association on a habitat level, but it could not reason the fine pattern of the plant communities on the same soil class. Canonical correspondence analysis (CCA) was performed to investigate the relationship between the distribution of dominant species and soil parameters. Several soil parameters combined have a significant effect on the distribution of dominant species. In conclusion, we found that the formation of association types strongly depends on the soil characteristics of the area, and that it is closely related to it. However, in the formation of the fine mosaic pattern, the driving ecological factors are the microrelief and the length of the saturated or flooded soil conditions.

phytocoenology / soil factors / soil-plant relationships

Kivonat – Összefüggés a vegetációmintázat és talajok között nedves és üde-nedves gyeptársulásokon a Hanság és Tóköz területén (Magyarország). Kutatásunk a nedves rétek fitocönózisának, finommozaikos mintázataért felelős okok felderítésére irányult. A vizsgálatok a Kisalföld nagytáján, ezen belül a Tóközben és a Hanság egykori lápmedencéiben történtek, Magyarországon. A választott mintaterületeken cönológiai felméréseket végeztünk, melyek felvételi adatait statisztikai módszerekkel (TWINSPAN analízis) kiértékeltek. Elkészítettük a területek vegetációtérképeit. A kvadrátok közelében feltalajmintákat vettünk, melyeket laborvizsgálatoknak vetettünk alá, valamint Pürckhauer-féle szűrőbotos mintavevő segítségével 1 méteres talajszelvényeket vettünk a talajtípusok helyszíni leírásához. Beszereztük a vizsgálati területek felületmodelljeit, melyekből szintvonalas térképeket generáltunk így a domborzati eltéréseket össze tudtuk vetni a növényzet mintázatával. Megállapítottuk, hogy a két meghatározó növényzettípus közül a mocsárrétek a típusos réti talajokhoz, míg a magassárrétek a lápos réti talajokhoz kötődnek. A két talajtípus átmenetein a magassárrétek alcsoportja a meghatározó típus. Kimutattuk, hogy a talajtípus csak

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élőhely szinten (láp-, magassás, mocsárrét) határozza meg a növényzetet, az asszociációk egymással kialakított finom mintázataért nem felelős. Az azonos talajtípusokon kifejlődött eltérő növénytársulások hasonló képet mutattak, így a finom mintázat kialakulását nem magyarázzák. Kanonikus korrespondencia analízissel (CCA) kerestük a domináns fajok elterjedésének és a talajtani adottságoknak a kapcsolatát. Megállapítottuk, hogy a több tényező együttesen alakítja a fajok elterjedését. Összegezve, a társulástípusok kialakulása erősen függ a terület talajtani viszonyaitól, azzal szoros kapcsolatban áll. Azonban a finommozaikos mintázat kialakulásában a mikrodomborzat változatossága és az ezzel együtt járó vízborítottság különbség mértéke lehet a meghatározó ökológiai faktor.

fitocönológia / talajtulajdonságok / talaj-növény kapcsolatok

1 INTRODUCTION

The plant communities and soils of wet and wet-mesic grasslands formed water-rich environments (Scott et al. 1998). The saturated soil conditions and periodical flooding are important factors in these habitats. The common soil classes are Histosols (marsh soils) and Gleysols (meadow soils). In wet habitats, Histosols are formed as organic material accumulates, which is the result of persistent water saturation, anaerobic soil conditions, and the slowed decomposition of plant debris (Stefanovits et al. 2010). Wet to mesic habitats are affected by unsaturated soil conditions for shorter or longer periods of time, and flooding rarely occurs. The topsoil is well aerated under more mesic conditions, while wetter conditions lead to the accumulation of organic matter in the form of muck.

The distribution of species and their biomass production are highly determined by soils (Janssens et al. 1998, Duranel et al. 2007, Seabloom et al. 2021), but plants also affect the soils. Several studies aimed to answer whether this dynamic relationship could be detected between soil properties and vegetation diversity, but the relationship of soils and vegetation pattern is not explained completely (Scott et al. 1989, Ma et al. 2021).

The species composition of wet grassland plant associations is ruled by the nutrient contents, but pH, organic carbon content (TOC), and soil bulk density (BD) also play important roles (Bedford et al. 1999). Extremely low BD ($< 0.25 \text{ g}\cdot\text{cm}^{-3}$) signifies histic conditions where the nutrient levels are generally low while there is a vast amount of TOC. Higher BD informs us about the different porosity of the soil and about the different water regime. Low pH can indicate the limitation of nutrient uptake or toxic conditions, while slightly acidic or neutral values are seen under more aerated soil conditions (Ma et al. 2021). Along the changes of O_2 and redox gradients, Josselyn et al. (1990) and Pennington – Walters (2006) observed patterns in the composition of plant vegetation. Even soil microbial communities have a strong relation with soil conditions and vegetation characteristics (Li et al. 2021). Michener (1983) investigated catenas in the northeastern part of United States regarding the composition and diversity of plant associations. He discovered a close relationship between soil zonation and plant community patterns. Bartha et al. (1996) described the relationship of site parameters and plant associations in a meadow in Bozsok (Zsidó-rét). The geomorphology of the mesotrophic wet meadow involved in the research is diverse, and many associations are represented in the area accordingly. Bartha et al. (1996) found that the zonation of the vegetation closely followed the zonation of the habitat and of the soils. Rajkai (1978) reports on his research in the floodplain of the Szilas stream, in which he states that the water regime of the different soil classes is closely related to the species composition of the plant association developed on their surface. Microtopography was found to be an important organizing structure of vegetation pattern (Diamond et al. 2019). Diamond et al. (2020) even revealed a correlation between soil chemical properties and microtopography. These studies showed that plant associations and soil types, especially soil

chemical properties, and relief have a close relationship. Nevertheless, many blank spots remain.

Focusing on the plant communities of wet and wet-mesic grasslands, there are generally numerous associations which are mixtures of lowland or colline plant associations. They form stripe- or mosaic complexes with each other. Several different associations were found in the plains, especially on the wet and wet-mesic grasslands of Hanság and Tóköz. Zólyomi (1934) presented the plant associations and habitat of Hanság. Jármai-Komlódi (1960) described the plant associations of south Hanság. Keszei – Takács (2008) completed an overview of north Hanság habitats.

Wetlands and wet grasslands are disappearing all over the world (Hu et al. 2017). In Hungary, the proportion of these habitats is in constant decline due to climate change and anthropogenic effects (Kovács 1957, Tasi et al. 2014). The longer and more frequent dry periods have been especially detrimental (Borhidi – Sánta 1999, Bartholy et al. 2011). Grassland and meadows are usually grazed or mowed, but the danger of overuse is always present (Janisova et al. 2013, Swacha et al. 2018, Bíró et al. 2020). Recording the current state of these habitats is also an important motivation.

The plant associations of the research area exhibited a mosaic pattern. Our research aims to find the reasons behind the observed pattern. We wanted to answer the following research questions: (1) Does the plant association pattern follow the soil diversity of the research area? (2) Is there any soil parameter or groups of parameters that show direct relationship with species composition? (3) Is there a relationship between the vegetation pattern and microrelief?

2 MATERIALS AND METHODS

2.1 Study area

The Hanság and Tóköz (Csorna plain) are plains formed by tectonic subsidence and subsequent refilling of the area. Non-runoff areas are common due to topography. Groundwater is generally close to the surface. The variability of the microrelief can have a large influence on vegetation. According to the Köppen-Geiger classification, the region is characterised by a warm temperate, fully humid, and hot summer climate (*Cfb*). (Berki et al. 2019a, b). Between 1961 and 2010, the annual mean temperature was 10.2°C and the annual rainfall was 564 mm. June is the wettest month. The forest aridity index (FAI) is 6.70, indicating a forest climate class with Turkey oak and sessile oak (Führer et al. 2019a, b).

The treeless plant communities of the micro-regions are characterized by mesotrophic wet meadows, non-tussock tall-sedge beds, mesotrophic wet meadows, and their transition parts. There are also mesic hay meadows, uncharacteristic wetlands, uncharacteristic mesic grasslands, and uncharacteristic dry and semi-dry grasslands that have become uncharacteristic due to anthropogenic effects. Our research investigated relatively small (< 10ha) areas in which the current treeless plant associations show a high degree of mosaic pattern. The visible difference in species composition was obvious even in the flat meadows. Depending on the location, the various treeless associations alternated in the form of stripe complexes or mosaic complexes. Closely related coenoses are also separated in most cases (based on physiognomy, species composition).

2.2 Methods of botanical survey and soil investigation

We conducted field surveys within the village boundaries of Barbacs and Osli in 2020 (Figure 1). The vegetation sampling is based on a modified Braun-Blanquet method – plant

cover percentage is used (Braun-Blanquet 1932). During the survey on the research area previously described, seven association types were searched and sampled. As a first step, satellite imagery was obtained and observed to delineate the plant community units. Then the field assessment, where the actual plant communities were identified and delineated, began. Altogether 94 relevés were collected. In 21 relevés, topsoil sampling and description were also performed: three relevés from every plant association. The relevés were 5×5 meters. The location of the relevés was recorded by GPS-based point determination using a Trimble Geo XT field computer.

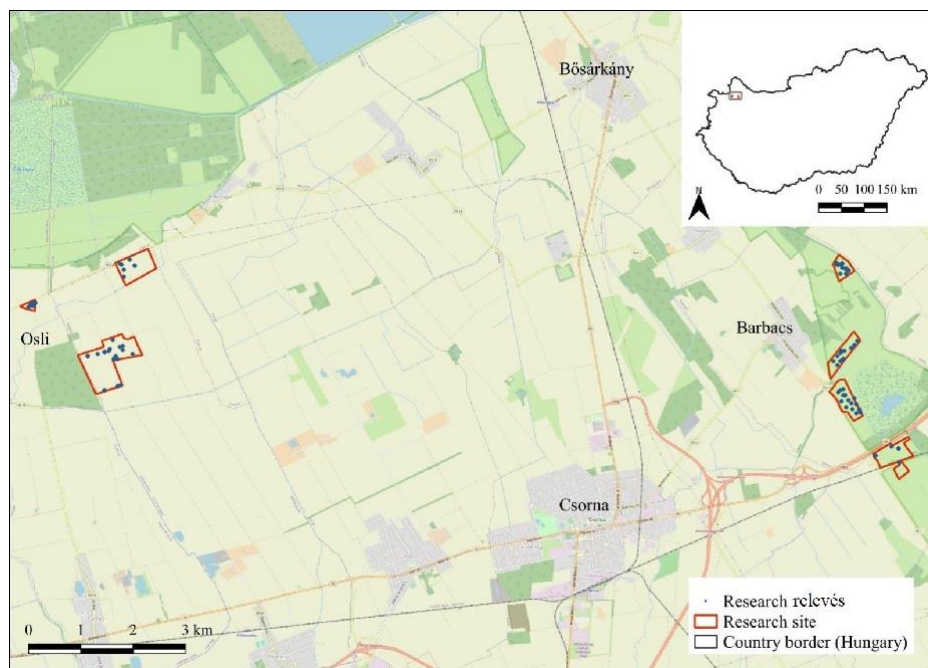


Figure 1. Map of the study area with the research sites and relevés

The nomenclature of plant species follows the work of Király (2009). We considered Borhidi's (2003) work relevant in determining the associations. During the survey, we prepared a species list of the plants within the relevé and estimated the total cover, the percent of the open soil surface and the litter cover, and average vegetation height.

To determine the genetic soil type, we took soil profiles with a Pürckhauer sampler at the 21 selected relevés. The properties of genetic soil levels were recorded at the sites during the description. When naming soil types, we use both the Hungarian genetic system (Stefanovits 2010) and the nomenclature of the World Reference Base for Soil Resources (WRB) (FAO 2015). During field days, momentary soil moisture content (VWC) was measured at depths of 0-10 cm (VWC1), 10-20 cm (VWC2), and 20-30 cm (VWC3) (Aquaterr M-300) with three repetitions at every relevé. We took average soil samples from the upper 10 cm layer of the soil for laboratory tests on relevé level. Concurrently, 100 cm³ samples were also taken with sampling cylinders to calibrate the measured VWC and to measure the bulk density (BD).

2.3 Data processing, laboratory soil analysis and statistical testing

We classified the data collected during the vegetation survey into coenological tables. The coenological recordings were taken using the TURBOVEG database management software (Hennekens – Schaminée 2001), and then the statistical evaluation of the data was performed with the JUICE software package version 7.1 (Tichý 2002). The classification is based on the modified TWINSpan method (Roleček et al. 2006). During the analysis, the maximum number of divisions was seven and the analysis was run using the average of the Simpson

index of dissimilarity as a measure of within-group heterogeneity. The background information belonging to the formed groups (total cover (%), litter cover (%), etc.) come from the field observations. The diagnostic, constant, and dominant species of the established groups were defined following the method of Chytrý et al. (2002). The range of diagnostic species was determined by calculating the fidelity values based on the coefficient Φ . Fidelity values were calculated only for species that showed non-random occurrence across the clusters according to the Fisher's exact test ($P < 0.05$). The use of numerical vegetation classification aims to reduce the subjective factors of the expert-based classification. We give a brief summary of both classifications, but in the later analyses we use the vegetation groups based on the modified TWINSpan analysis.

We performed laboratory testing of the soil samples based on the methodological recommendations of Bellér (2000) in the soil laboratory of the Institute of Environment and Earth Sciences of the University of Sopron. The undisturbed samples from the sampling cylinders were measured at the end of the field days and then dried at 105 °C for three days, after which they were measured again. In this way, we obtained VWC for calibration, and BD. The average or disturbed samples – collected near the cylinders – were dried at room temperature. After that, the skeletal parts, roots, and snail shells were removed from the samples. The pH (H₂O) of the prepared soil samples was measured in a 1:2.5 soil:distilled water suspension (Motsara – Roy 2008). The determination of the ammonium-lactate-acetic acid soluble (AL) potassium and phosphorus contents is based on the methodology of Egnér et al. (1960), which showed the phosphorus (PAP) and potassium (PAK) contents that are available for the vegetation. Finally, the organic carbon content (TOC), and the total-nitrogen (TN) and sulphur (TS) content of the soils were determined according to international standards (ISO 10694: 1995 and ISO 13878: 1998) using the Elementar Vario MAX CNS elemental analyser (Elementar Analysensysteme, Langenselbold, Germany).

We used a digital elevation model (DEM) from the Lechner Knowledge Centre called DDM-5 to visualize elevation, which was generated by digitizing 1:10000 scale topographic maps (Telbisz et al. 2013). Digitalization of the on-site drawn vegetation maps and visualization of the DEM was achieved by QGIS, version 3.18. Since elevation above sea level is not a good measure of microtopography in the present case – it provides no information about whether the given point is a bottom of a ditch or a top of a hummock – derived models are used to quantify the microrelief. The DEM is calculated into normalised elevation model and slope model. According to Diamond et al. (2019) hollows tend to have less-than-average elevation and less-than-average slope. This classification was compared with the manual delineation of hollows. The automated delineation has 14.6 % root mean square error (RMSE) against the manual one. At the level of TWINSpan groups, the calculated values were compared to determine potential significant difference between them. For this purpose, one-way analysis of variance (ANOVA) was applied with post-hoc Tukey-test.

R environment (R Core Team 2014) provided the further place for statistical analyses. Pairwise correlation was calculated between soil parameters with Bonferroni-adjusted P values. Average values of the soil parameters were calculated at the level of the TWINSpan groups. The soil parameters of the relevés assigned to the TWINSpan groups were compared via ANOVA and homogenous groups were separated with Tukey's honestly significant test. To investigate the relationship between the soil parameters and the distribution of the dominant plants (cover percentages) among the TWINSpan groups, canonical correspondence analysis (CCA) (Legendre – Legendre 2012, Oksanen et al. 2020) was applied. The soil parameters which showed high linear dependency were eliminated from the CCA; for this purpose both correlation analysis and calculation of variance inflation factor

(VIF) was performed. Variables which showed multicollinearity ($VIF > 5$) were left out from the CCA. Only tests with $P < 0.05$ are named as significant.

3 RESULTS

3.1 Results of the botanical survey

We investigated a total of seven association types in the study areas that were described in previous studies:

1. *Glycerietum maximae* Hueck 1931;
2. *Galio palustris-Caricetum ripariae* Bal.-Tul. et al. 1993;
3. *Caricetum acutiformis* Eggler 1933;
4. *Caricetum gracilis* Almquist 1929;
5. *Caricetum distichae* Steffen 1931;
6. *Cirsio cani-Festucetum pratensis* Májovsky – Ružičková 1975;
7. *Carici vulpinae-Alopecuretum pratensis* (Máthé – Kovács M. 1967) Soó 1971 corr. Borhidi 1996;

Table 1 introduces the average characteristics of the relevés on the plant association level. Association types typically appear together in the form of stripe or mosaic complexes in the areas. They are well separated by their species composition and physiognomy, but usually there is a 1-8 m wide transition zone of adjacent associations where these associations are mixed. At gradually rising elevation, the associations follow each other in a stripe-like manner, while in flat areas they appear in patchy patterns.

Table 1. Average characteristics of the plant associations (mean (standard error of mean))

Plant association	Nr. of relevés (pcs.)	Avg. Nr. of species (pcs.)	Plant coverage (%)	Litter coverage (%)	Exposed soil surface (%)	Average height (cm)
<i>Galio palustris-Caricetum ripariae</i>	13	6 (1.04)	75 (2.56)	4 (1.17)	7 (2.37)	60 (2.91)
<i>Caricetum gracilis</i>	25	9 (0.80)	77 (2.10)	2 (0.52)	5 (1.61)	51 (1.68)
<i>Caricetum distichae</i>	9	12 (1.02)	78 (2.04)	3 (1.08)	10 (3.85)	37 (3.12)
<i>Glycerietum maximae</i>	8	6 (0.73)	66 (3.10)	5 (2.45)	14 (3.97)	56 (6.44)
<i>Caricetum acutiformis</i>	10	5 (0.57)	79 (2.56)	3 (1.09)	9 (3.58)	66 (4.74)
<i>Cirsio cani-Festucetum pratensis</i>	12	22 (1.29)	82 (2.71)	2 (0.59)	7 (2.73)	50 (2.34)
<i>Carici vulpinae-Alopecuretum pratensis</i>	17	19 (0.96)	89 (3.14)	2 (0.52)	1 (0.31)	51 (3.29)

3.1.1 Vegetation of wet sites

The *Glycerietum maximae* association is typically associated with the marginal zone of watercourses, but it also appears in smaller hollows in wet meadows. Its species number is

very low; the predominance of *Glyceria maxima* is obvious. The typical species are *Symphytum officinale*, *Lythrum salicaria*, and *Ranunculus repens*. As the habitat becomes drier, the *Galio palustris*-*Caricetum ripariae* association becomes dominant. The boundary between the two associations is usually marked by a sharp difference – transition happens in 1-2 m – due to the frequency of dominant species cover, which is usually characterized by a homogeneous carpet-like setting. In addition to the predominant *Carex riparia*, some constant elements are *Lysimachia vulgaris*, *Persicaria amphibia*, and *Symphytum officinale*. The *Caricetum acutiformis* association appears in almost identical habitats. The two associations differ most obviously in their dominant species; their appearance is similar. Moving away from the water, an association of *Caricetum gracilis*, which is more species-rich, more resistant to abiotic and biotic stress, is present. While the previous associations appear mostly as smaller spots or narrow stripes, these acute sedge associations are extensive. Their appearance is diverse, several compositions can be observed, from completely homogeneous acute sedge spots to broken-up, mosaic, and significantly more diverse settings. At some places, the *Caricetum distichae* association is wedged into the acute sedge associations as small spots and does not form large, connected stands. Typically, the patch area does not exceed 50 m². The species diversity of both types of associations is moderate. In addition to *Carex acuta*, *C. disticha*, *Cirsium brachycephalum*, *C. canum* and *Galium palustre* are typical. Both types (4-5) are more resistant to mowing (i.e., cutting and removal of the cut biomass) than types 1-3. As a result of improper grassland management, associations 1-3 are easily transformed, most often into association type 4 (Figure 2 A), especially if types 1-3 are on edge habitats.

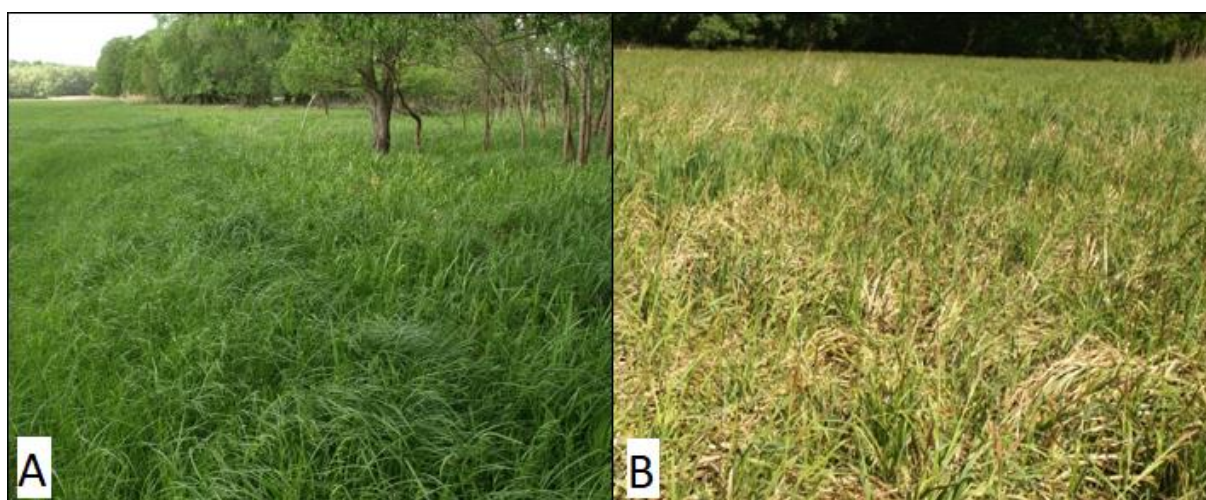


Figure 2. Effects of mowing (A) and accumulation of dry biomass on the soil surface (B)

The lack of grassland management makes the coenoses species-poor, mostly as a result of dry biomass accumulation (Figure 2 B), which makes many species unable to sprout. If sufficient water is available, the accumulation of sedge biomass is insignificant. However, this problem becomes common as the areas dry out.

3.1.2 Vegetation of wet-mesic sites

With the further decrease of the length of saturated periods, the dominance of sedge species also decreases; they are replaced by grass species. Typical associations in these areas are *Cirsio cani*-*Festucetum pratensis* and *Carici vulpinae*-*Alopecuretum pratensis*. Borhidi (2003) treats the association *Carici vulpinae*-*Alopecuretum pratensis* as a member of the *Deschampsion caespitosae* group. He mentions that the *Ranunculo repentis*-

Alopecuretum pratensis – which is poorer in *Magnocarion* species – is also closely related to it or that they are the same association. A more recent study sorts the *Ranunculo repentis-Alopecuretum pratensis* association into the *Arrhenatherion* group as a mesic-wet type (Lengyel et al. 2016). The most common habitats are colline and mountainous valleys. This association has a similar species composition as *Carici vulpinae-Alopecuretum pratensis*, but the proportion of the species of semi-dry grasslands and colline habitats is much higher. Therefore, we identified the more water-tolerant associations of wet mesotrophic wet meadows as *Carici vulpinae-Alopecuretum pratensis*.

The former is a typical plant community of mesic habitats; the latter of wet-mesic habitats. In many cases, they connect to each other via broader (4-8 m) transition zones. Their species composition is characterized by the fact that they do not have typical character species. Dominant species are generalists with a wide range of tolerance, so in many cases it is difficult to appropriately differentiate these plant associations. Typical species of the *Cirsio cani-Festucetum pratensis* association include *Festuca pratensis*, *Poa pratensis* and *Rumex acetosa*. Its stands at the Hanság are more degraded; they lack rare species. The *Carici vulpinae-Alopecuretum pratensis* association is less disturbed, even *Stellaria palustris* appearing in its stand. Typical species are *Alopecurus pratensis*, *Ranunculus acris*, and *Lathyrus pratensis*.

3.2 Results of the modified TWINSpan analysis

According to the analysis results, the investigated plant communities do not differ as much from each other as we identified in the field. Of the six clusters formed (Figure 3).

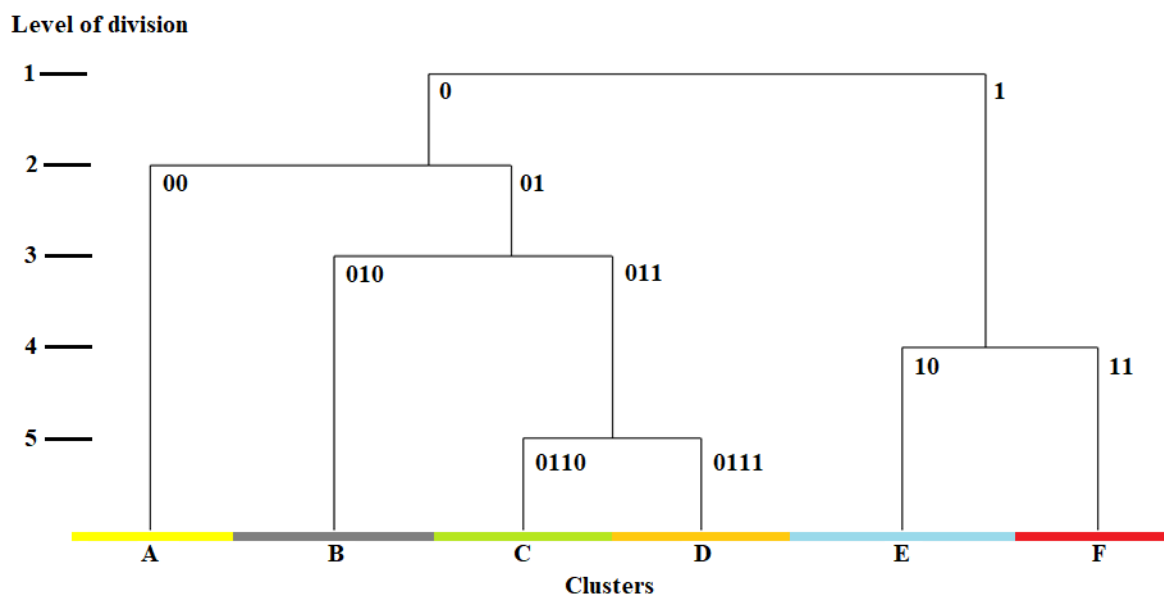


Figure 3. Modified TWINSpan dendrogram of the 94 relevés

The first division brought the separation of the non-tussock tall-sedge beds (0) and the mesotrophic wet meadows (1). In the second division, the non-tussock tall-sedge beds (0) were divided into lesser groups: *Caricetum gracilis* × *Caricetum distichae* group (00) and a combination of *Galio palustris*-*Caricetum ripariae* group (01). This group (01) was divided into two subgroups: *Caricetum acutiformis* × *Caricetum ripariae* group (010) and the mixed group of *Galio palustris*-*Caricetum ripariae* associations (011). Group (011) collected the associations of wet and mesic habitats. This group is separated into two: the wet habitats were characterised by the *Galio palustris*-*Caricetum ripariae* × *Glycerietum maximae* group (0110)

and the wet-mesic habitats were populated by *Galio palustris*-*Caricetum ripariae* × *Caricetum gracilis* group (0111).

The division of mesotrophic wet meadows (1) partitions into two subgroups. Both subgroups have transient characteristics. Their separation is caused by the different moisture regimes; group (10) occurs under more wet conditions while group (11) prefers less wet conditions.

Table 2 summarises vegetation characteristics of the formed TWINSpan groups and the distribution of relevés between the two classification systems. The detailed interpretation of the TWINSpan groups is in the following subsections.

Table 2. Average vegetation characteristics of the TWINSpan groups (mean (standard error of mean)) and the distribution of relevés between the plant associations and TWINSpan groups (CARR - *Galio palustris*-*Caricetum ripariae*, CARG - *Caricetum gracilis*, CARD - *Caricetum distichae*, GLY - *Glycerietum maximae*, CARA - *Caricetum acutiformis*, FES - *Cirsio cani*-*Festucetum pratensis*, ALO - *Carici vulpinae*-*Alopecuretum pratensis*, SUM - summary)

Groups	Perc. cover	Litter cover	Exposed soil surface	Avg. height	Avg. nr. of species	Nr. of relevés (pcs.)							
						C A R R	C A R G	C A R D	G L Y	C A R A	F E S	A L O	S U M
	(%)	(%)	(%)	(cm)	(pcs.)								
00	80 (3.03)	1 (0.50)	4 (1.69)	44 (2.09)	10 (0.75)		12	2					14
010	76 (2.28)	3 (0.76)	7 (2.18)	62 (3.40)	4 (0.39)	3	4			10			17
0110	71 (2.71)	5 (1.54)	11 (2.68)	59 (3.81)	6 (0.55)	7			8				15
0111	76 (1.50)	3 (0.69)	9 (2.83)	51 (3.24)	10 (0.77)	3	8	4					15
10	85 (2.95)	2 (0.63)	4 (1.65)	48 (3.06)	17 (0.84)		1	3			1	14	19
11	85 (2.85)	2 (0.50)	6 (2.41)	50 (2.13)	22 (0.93)						11	3	14

3.2.1 *Caricetum gracilis* × *Caricetum distichae* group (00)

This cluster shows a transitional character. The two associations usually form mosaic complexes with each other. Small patches (~50 m²) of *Caricetum distichae* are wedged into the carpet-like *Caricetum gracilis* stands. There is considerable overlap in species composition but there are differences in their dominant species and physiognomy.

Diagnostic species: *Caltha palustris*, *Cardamine pratensis*, *Carex acuta*, *Carex vesicaria*, *Carex vulpina*, *Equisetum palustre*, *Lysimachia nummularia*, *Myosotis scorpioides*, *Persicaria dubia*, *Poa palustris*, *Ranunculus repens*.

Constant species: *Lychnis flos-cuculi*, *Rumex acetosa*, *Symphytum officinale*, *Taraxacum officinale*.

Dominant species: *Carex acuta*, *Carex disticha*.

3.2.2 *Caricetum acutiformis* × *Caricetum ripariae* group (010)

This group is created from two plant associations which are easy to distinguish in the field. However, both can be characterized as species-poor associations of hollows and wetter areas with a carpet-like setting. The associations share several species, and the physiognomy of the plant communities are determined by the dominant species. In most cases, *Carex riparia* and *C. acutiformis* are present together, but the dominant one has much higher cover percentage and more individuals. There is no evidence of codominance, which would imply the aggregation of the two associations. The TWINSpan method aggregated these associations since their relevés were homogenous and since they have almost the same species with similar cover percentages. The difference is only shown in the dominant species (cover percentages).

Diagnostic species: *Carex acutiformis*, *Lythrum salicaria*.

Constant species: *Carex riparia*, *Lysimachia vulgaris*, *Symphytum officinale*.

Dominant species: *Carex acutiformis*, *Carex riparia*.

3.2.3 *Galio palustris*-*Caricetum ripariae* × *Glycerietum maximae* group (0110)

This is a transitional group of the wet areas. The group of mixed plant communities (0110) contains relevés of *Galio palustris*-*Caricetum ripariae* and *Glycerietum maximae* associations. This indicates that the assessment of differences between the investigated associations is not uniform. There is no significant difference in the species combination of the two types. However, the dominant species determines the appearance of the association, based on which they can be easily distinguished in the field. The program creates new groups based on the heterogeneity between the relevés. As these are quite similar based on their species composition, the analysis does not separate them into separate subgroups.

Diagnostic species: *Carex riparia*, *Glyceria maxima*, *Persicaria amphibia*, *Schoenoplectus lacustris*, *Stachys palustris*, *Urtica dioica*.

Constant species: *Iris pseudacorus*, *Ranunculus repens*, *Symphytum officinale*.

Dominant species: *Carex riparia*, *Glyceria maxima*.

3.2.4 *Galio palustris*-*Caricetum ripariae* × *Caricetum gracilis* group (0111)

This group is found in the transition zone of the wet and wet-mesic group. It is characterised by less wet conditions than in the case of 0110 group. These two groups often form stripe complexes or patch-complexes in micro-basins. Group 0111 is more species-rich than 0110 or the formerly introduced groups; however, it is more species poor than *Caricetum gracilis*. The species of the two associations mix equally and the two dominant species are often codominant.

Diagnostic species: *Agrostis stolonifera*, *Carex acuta*, *Cirsium arvense*, *Cirsium brachycephalum*, *Galium palustre*, *Iris pseudacorus*, *Persicaria amphibia*, *Phalaris arundinacea*, *Symphytum officinale*, *Thalictrum flavum*.

Constant species: *Cardamine pratensis*, *Carex riparia*, *Lysimachia vulgaris*, *Ranunculus repens*.

Dominant species: *Carex acuta*, *Carex disticha*, *Carex riparia*.

3.2.5 *Carici vulpinae*-*Alopecuretum pratensis* × *Caricetum gracilis* group (10)

This group of associations forms in the transition zone between mesotrophic wet meadows and non-tussock tall sedge beds and in the depressions of mesotrophic wet meadows. The presence of typical mesotrophic wet meadow species (*Alopecurus pratensis*, *Cardamine pratensis*, *Galium mollugo*) and an accumulation of aquatic species (*Iris pseudacorus*,

Phalaris arundinacea, *Symphytum officinale*) characterise the group. They are unstable plant communities, sensitive to changes in environment. The dominant species which is better adapted to the weather in a given year determines the community. They can experience significant change within a year.

Diagnostic species: *Alopecurus pratensis*, *Calamagrostis epigeios*, *Cardamine pratensis*, *Carex hirta*, *Carex otrubae*, *Cerastium tenoreanum*, *Festuca pratensis*, *Galium mollugo*, *Glechoma hederacea*, *Lychnis flos-cuculi*, *Phalaris arundinacea*, *Poa pratensis*, *Potentilla anserina*, *Potentilla reptans*, *Ranunculus repens*, *Taraxacum officinale*, *Vicia cracca*.

Constant species: *Cirsium arvense*, *Cirsium canum*, *Iris pseudacorus*, *Symphytum officinale*.

Dominant species: *Alopecurus pratensis*, *Carex disticha*, *Festuca pratensis*.

3.2.6 *Carici vulpinae-Alopecuretum pratensis* × *Cirsio cani-Festucetum pratensis* group (11)

The present cluster includes the typical mesotrophic wet meadows. In the absence of reliable character species, mesotrophic wet meadows are often difficult to distinguish from each other. They occur in a fairly wide range of habitats due to their broad-spectrum generalist species, which define the community. The observed *Cirsio cani-Festucetum pratensis* association is more species-poor than described by Borhidi (2003). The stands of the *Carici vulpinae-Alopecuretum pratensis* association are mostly small, with a wide transition to the mesotrophic wet meadows dominated by *Festuca* species. Considering the above-mentioned facts, it is understandable that they were not separated in the analysis. Nevertheless, we consider their field isolation to be necessary because they indicate the changes in the water balance of the habitat.

Diagnostic species: *Achillea millefolium*, *Anthoxanthum odoratum*, *Arrhenatherum elatius*, *Carex hirta*, *Carex praecox*, *Carex spicata*, *Cerastium brachypetalum*, *Cirsium canum*, *Colchicum autumnale*, *Dactylis glomerata*, *Daucus carota*, *Erigeron annuus*, *Festuca pratensis*, *Festuca rupicola*, *Fragaria viridis*, *Frangula alnus*, *Galium mollugo*, *Galium verum*, *Glechoma hederacea*, *Lathyrus tuberosus*, *Leontodon hispidus*, *Leucanthemum vulgare*, *Linaria vulgaris*, *Lotus corniculatus*, *Luzula campestris*, *Lychnis flos-cuculi*, *Myosotis arvensis*, *Myosotis ramosissima*, *Pastinaca sativa*, *Plantago lanceolata*, *Poa angustifolia*, *Poa pratensis*, *Potentilla reptans*, *Ranunculus acris*, *Rosa canina* s.s., *Rubus caesius*, *Rumex acetosa*, *Solidago gigantea*, *Veronica chamaedrys*, *Vicia hirsuta*, *Vicia tenuifolia*.

Constant species: *Alopecurus pratensis*, *Cirsium arvense*, *Potentilla anserina*.

Dominant species: *Alopecurus pratensis*, *Arrhenatherum elatius*, *Festuca pratensis*.

3.3 Results of soil analyses

During the field investigations, we described hydromorphic soils with topsoil of different thickness and organic matter (OM) content. Mollic Gleysols (meadow soils) were found in three cases (more mesic parts of the wet-mesic habitats). In wet habitats Histic Gleysols (histic meadow soils) were more common, which were present in 12 relevés. Transient types of the two soil types were found in six cases in wet-mesic habitats, especially in which wet character dominates and it associates with only a lower accumulation of OM. These are described as Mollic Gleysol (Hyperhumic). These soils have looser topsoil and higher OM

content (muck layer) than the described Mollic Gleysols, but they do not reach the requirements of histic properties.

The correlations between the individual soil parameters demonstrated that elevation and pH (H₂O) have no significant relationship with the other variables, except with each other ($r = 0.47$). All the other correlations proved to be significant. PAK shows a strong positive correlation ($0.50 < r < 0.60$) with PAP and TS, while it has a medium positive correlation with TN ($r = 0.47$) and a negative one with BD ($r = -0.45$). PAP is correlated strongly ($r > 0.60$) positively with TOC, TN, TS, VWC1, VWC2 and VWC3 and negatively with BD ($r = -0.76$). TOC, TN, and TS have strong positive connection with each other ($r > 0.95$), and with the VWC too ($r > 0.84$). The relation of BD and TN, TS is described as strong negative ($r < -0.89$). Between BD and the VWCs the connection strongly negative ($r < -0.85$). The group of moisture contents (VWC1, VWC2, VWC3) have correlation coefficients above 0.95 with each other, which indicates a strong positive relationship.

TOC and BD show a strong negative relationship (Figure 4) and the soil profiles of different classes cluster along these parameters. In the case of Mollic Gleysols, the lower TOC is associated with a high BD value, which indicates that the humic character does not dominate, but a relatively high, above 7%, TOC was observed as a result of OM accumulation. In the transitional group, TOC jumps, above 10%, but does not reach 20%. In parallel, BD decreases. As the histic character became predominant, a high TOC of over 20% was measured as a result of organic matter accumulation, which is accompanied by a very low BD.

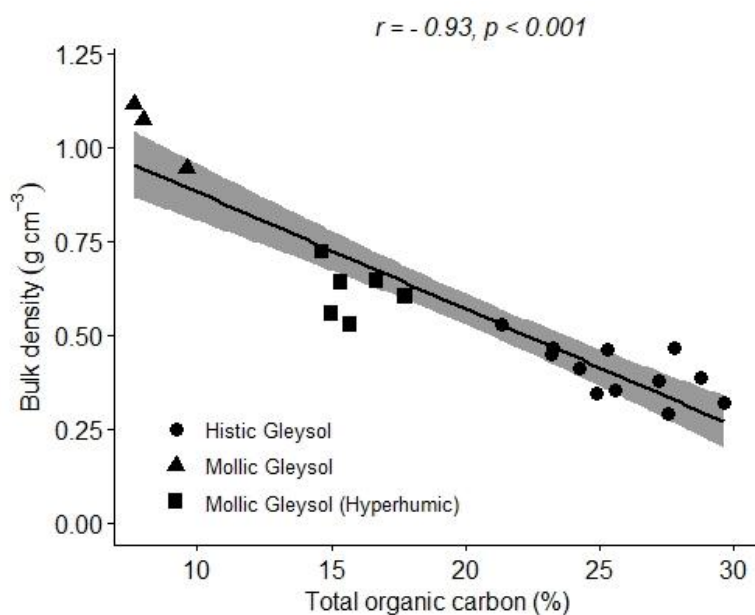


Figure 4. Relation of soil bulk density (BD) and total organic carbon (TOC) along different soil groups

3.4 Correlation between soil parameters and TWINSpan groups

There is a correlation between the soil classes and the TWINSpan groups (Table 2). On Mollic Gleysol, only group 11 can be found, while on Histic Gleysol, we typically find groups 010 and 0110, and group 0111. In the case of the transient Mollic Gleysol (Hyperhumic), the transient vegetation group 10 is predominant, but groups 00 and 11 also occur.

Table 2. Distribution of number of relevés among the TWINSpan groups and soil classes

Soil classes	TWINSpan groups					
	00	010	0110	0111	10	11
Mollic Gleysol						3
Mollic Gleysol (Hyperhumic)	1				3	2
Histic Gleysol		3	5	4		

The average soil parameters calculated for the TWINSpan groups are presented in Table 3. Since group 00 has only one observation, it was omitted from the analyses and the values of that one relevé are presented in the table. Similarly to the classification by soil groups, there is no sharp separation between the individual TWINSpan groups in terms of elevation, pH(H₂O), and PAK. For PAP, TOC, TN, and TS parameters, the TWINSpan groups are divided into two groups. 00, 010, 0110 and 0111 form a group dominated by the histic character, while groups 10 and 11 are found in the other group, where the meadow soil character predominates.

Table 3. Soil params of the different TWINSpan groups (mean (standard error of mean))

Soil parameters	TWINSpan groups						F	Sign.
	00	010	0110	0111	10	11		
Nr. of elements (relevés) (pcs.)	1	3	5	4	3	5		
Elevation (m)	110	110 ^a (0.000)	109 ^a (1.304)	109 ^a (0.408)	110 ^a (1.155)	111.4 ^a (0.678)	1.31	NS
pH (H ₂ O)	6.9	6.2 ^a (0.082)	6.4 ^a (0.173)	6.5 ^a (0.225)	6.5 ^a (0.24)	6.7 ^a (0.094)	0.87	NS
Plant Available P (mg 100 g ⁻¹)	16.2	18.3 ^a (0.789)	15.3 ^a (2.286)	14.7 ^a (1.462)	6.2 ^b (0.681)	5.3 ^b (0.691)	13.54	***
Plant Available K (mg 100 g ⁻¹)	17.5	30.0 ^a (4.693)	24.6 ^a (5.55)	19.7 ^a (1.975)	14.9 ^a (1.187)	16.4 ^a (1.392)	2.38	NS
Total Organic C (%)	15.7	27.3 ^a (2.007)	25.5 ^a (1.17)	25.0 ^a (0.864)	15.5 ^b (0.633)	11.7 ^b (2.058)	20.5	***
Total N (%)	1.5	2.2 ^a (0.132)	2.2 ^a (0.103)	2.2 ^a (0.037)	1.4 ^b (0.07)	1.0 ^b (0.18)	18.65	***
Total S (%)	0.3	0.6 ^a (0.099)	0.6 ^a (0.035)	0.5 ^a (0.027)	0.2 ^b (0.021)	0.2 ^b (0.034)	20.74	***
Bulk Density (g cm ⁻³)	0.5	0.4 ^a (0.042)	0.4 ^a (0.044)	0.4 ^a (0.019)	0.6 ^{ab} (0.047)	0.9 ^b (0.107)	10.22	***
Water Content 0-10 cm (%)	62.5	86.9 ^a (8.613)	95.0 ^a (2.165)	98.9 ^a (0.634)	78.0 ^a (11.018)	45.3 ^b (3.062)	22.39	***
Water Content 10-20 cm (%)	63.9	82.4 ^a (9.88)	91.9 ^a (3.547)	96.9 ^a (1.835)	72.4 ^a (14.601)	43.3 ^b (3.266)	13.49	***
Water Content 20-30 cm (%)	59.9	86.1 ^a (8.612)	92.5 ^a (2.593)	96.9 ^a (1.545)	75.5 ^a (12.35)	44.5 ^b (4.058)	16.86	***

Significance levels: 0 < *** ≤ 0.001 < ** ≤ 0.01 < * ≤ 0.05 < NS

^{abc} represents homogenous subsets according to Tukey's honestly significant difference test

According to the BD of soils, the subsets are similar to the former case, but group 10 forms a transition and can be classified into both groups. Moisture contents show a uniform picture; only group 11 deviates from the other groups.

CCA was performed to show the correspondence of the main environmental factors with the composition of dominant plant species, (Figure 5). Soil and topographical variables were represented as arrows (eight altogether). Arrow length indicates the importance of the environmental variable. To avoid multicollinearity, variables showing higher variance inflation factors than five were omitted. The analysis was based on 21 relevés pictured by points and coloured according to their TWINSpan group. The plant species were indicated by crosses. The location of the plant species relative to the arrows or axes represent the environmental conditions or gradients associated with the occurrence of the species.

The CCA model proved to be significant according to the permutation test ($F = 1.748$, $P = 0.004$). The total inertia is 4.746 from which 53.8% was described by the constrained axes. The first axis explained 18.4% of the total variation (34.2% of the constrained inertia), while the second axis covered 14.9% of the total inertia (27.6% of the constrained one). The coefficient of multiple determination (R^2) is 0.538 and the adjusted coefficient of multiple determination ($R^2_{adj.}$) is 0.234. The species – environmental correlation is strong, $r = 0.95$ in the case of the Axis 1 and $r = 0.89$ for Axis 2.

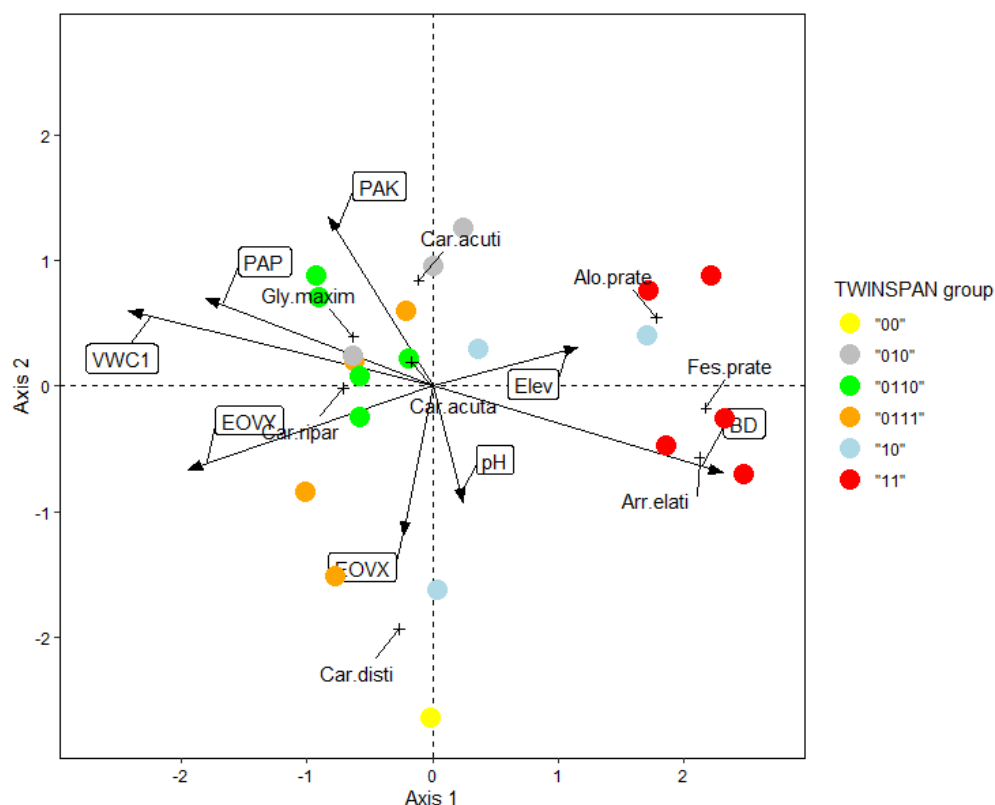


Figure 5. Results of the Canonical Correspondence Analysis (CCA) between the soil parameters (arrows) and cover percentage of the dominant species of the TWINSpan groups (crosses), points represent the relevés grouped by the TWINSpan groups. Abbreviations: Elev: Elevation (m), EOYX and EOYX: longitude and latitude in HD72 6 EOY reference system, pH: pH (H_2O), PAP: Plant Available Phosphorus ($mg\ 100\ g^{-1}$), PAK: Plant Available Potassium ($mg\ 100\ g^{-1}$), BD: Bulk Density ($g\ cm^{-3}$), VWC: Volumetric Water Content of soil layer between 0 and 10 cm (%), Alo prate: *Alopecurus pratensis*, Arr. elati: *Arrhenatherum elatius*, Car acuta: *Carex acuta*, Car acuti: *C. acutiformis*, Car dista: *C. disticha*, Car ripar: *C. riparia*, Fes prate: *Festuca pratensis*, Gly maxim: *Glyceria maxima*

The most important factors are BD, VWC, EOXY, PAP, and PAK. The first axis has a strong positive correlation with BD ($r = 0.818$) and strong negative with VWC1, EOXY, PAP ($r = -0.856, -0.687, -0.639$ respectively) and medium positive with elevation ($r = 0.409$). The second axis was affected mostly by PAK ($r = 0.446$) and medium negative correlation was shown with EOXY ($r = -0.394$) and pH ($r = -0.305$).

3.5 Results of vegetation mapping

The reason for the fine mosaic pattern of vegetation formed in flat areas should also be investigated in the microrelief differences. Therefore, we fitted 5×5 m resolution digital elevation models to the study areas and made a comparison with the pattern of vegetation patches surveyed during vegetation mapping. The vegetation patches and the fine-scaled (10 cm increase in elevation) equiheight lines coincide in several cases (Figure 6).

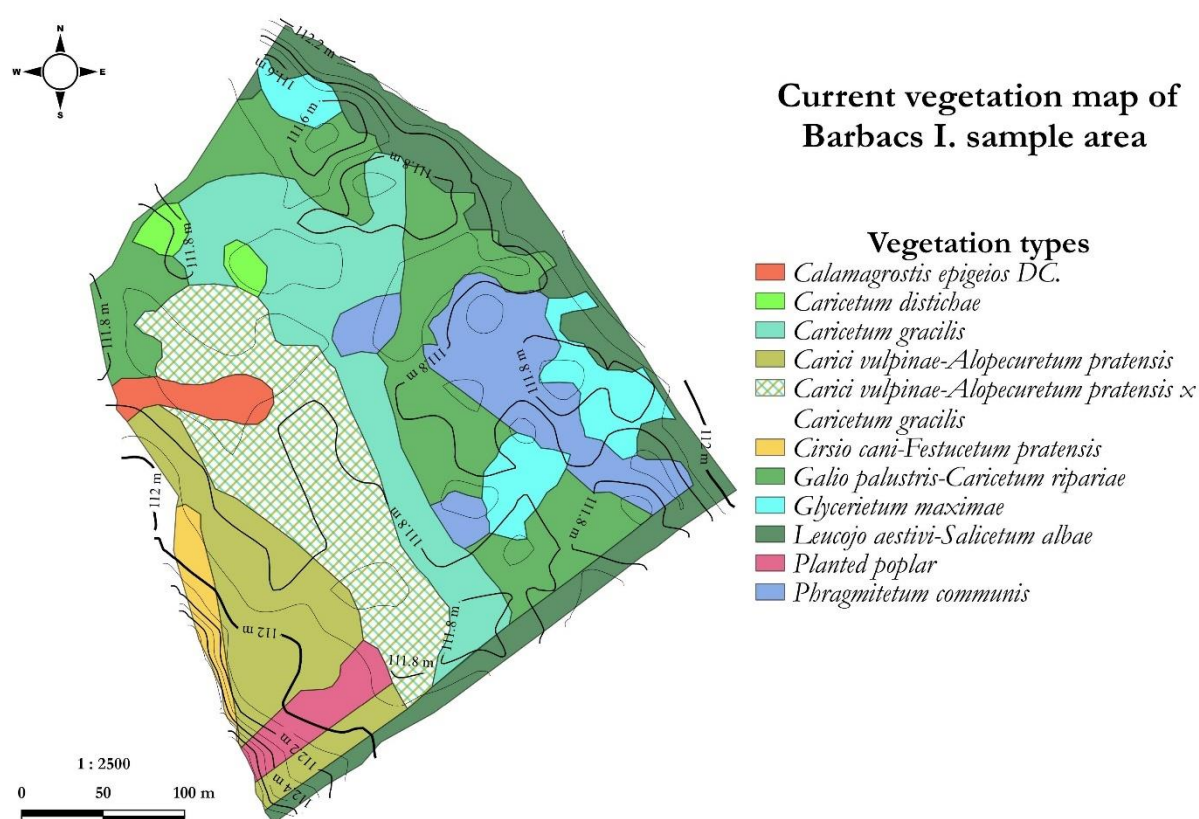


Figure 6. Current vegetation map of Barbacs I. sample area

The normalised elevation values of the TWINSpan groups differ significantly ($F = 32.94, P < 0.001$). There are three subsets separated by Tukey's test. TWINSpan group 00, 010, 0110, and 0111 are the ones which have average values lower than 0. Group 10 is a transient group and group 11 has the highest values and highest average. Normalised slope values show a different image. Significant difference among the groups is evident ($F = 16.67, P < 0.001$). The lowest values are accompanied with group 00 and 0111. Group 0110 shows a transition between subset a and b. Subset b (TWINSpan group 010 and 10) are in the mid-range, while group 11 has again the highest average (Figure 7).

The TWINSpan groups are assigned with the category of hummock or hollow according to the combined models of normalised elevation and slope on the level of relevés. The groups showed considerable differences ($F = 18.04, P < 0.001$). Tukey's test divided the group into

two subsets. TWINSpan group 00, 010, 0110, and 0111 are assigned to the hollow subset and TWINSpan group 10 and 11 classified into the hummock subset. TWINSpan group 00 has relevés only in hollows, 0110 and 0111 have three and one hummock relevés respectively while the rest of the relevés are hollows. TWINSpan group 010 has five hummock and 12 hollow relevés, group 10 has a similar distribution but with swapped groups (13 hummocks and six hollows). Group 11 has only hummock relevés.

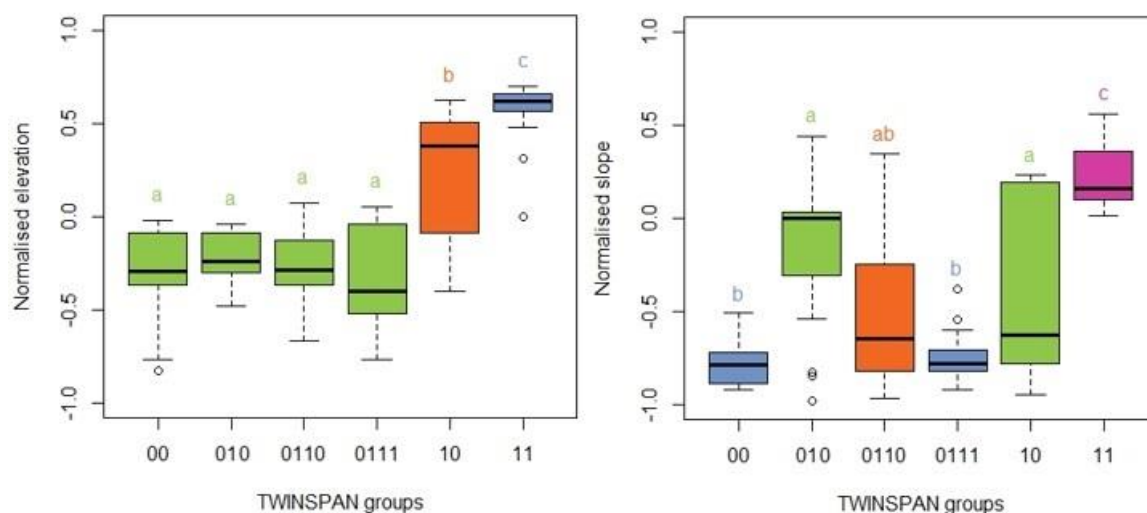


Figure 7. Normalised elevation and slope boxplots of the different TWINSpan groups. Groups with different colours are significantly different.

4 DISCUSSION

During the vegetation mapping and the more detailed investigation, we found the earlier mentioned seven (i.e., subsection 3.1) plant associations (Zólyomi 1934, Járαι-Komlódi 1960, Keszei-Takács 2008). The recorded relevés went under a TWINSpan analysis, which resulted in six association groups. These groups overlap; the numerical analysis aggregates closely-related plant communities e.g., *Galio palustris*–*Caricetum ripariae* × *Glycerietum maximae* (0110) group. These two associations differ only in the dominant species. Our assumption is that the TWINSpan method lowers the subjectivity of the expert-based description, and it provides more reliable data for further analyses. Beside the TWINSpan analysis, other methods could be used and compared to classify the relevés.

The soil survey revealed different forms of Gleysols, which is the typical soil class of wet and wet-mesic meadows. The soil groups differed in nutrient contents, BD values, and VWCs, but not in pH, elevation, and PAK. Similar results are presented by Heil et al. (2008), but they found significant difference between soil groups and pH values. This is also supported by Ma et al. (2021) and Li et al. (2017). The soil groups spread among the TWINSpan groups following a water gradient. Soils with more moisture content were found under more water tolerant TWINSpan groups. Li et al. (2017) reported similar findings. The difference of the soil parameters of the TWINSpan groups followed a similar pattern as in the case of WRB soil groups, except PAP, which showed significant difference only among the plant community groups. P content was found to be an important factor in plant composition of a site in several studies (Bigelow – Canham 2002, Amorim – Batalha 2007, Hammersmark et al. 2009, Mellado – Zamora 2015, Onur – Suha 2016). The plant associations follow the changes of the soil classes, but the finer pattern of the plant composition is not explained by the soil groups (Research question 1). The higher number of relevés and the periodical returns

to the same relevés could represent a more detailed relationship between the soils and plant communities. This can also help the land managers to set the optimal timing of mowing or grazing, e. g. only after the seeding of protected species.

The distribution of relevés according to their dominant species are organised along two gradients. The first axis represents soil porosity or wet to dry gradient. This axis separates the relevés of hollows, ditches, and the ones which are located on relatively elevated places. The species on the positive end of Axis 1 are typical species of mesic meadows, while the species around the origin are found in wet meadows. Jager et al. (2015) and Li et al. (2017) found soil physical parameters crucial for the distribution of plant communities. The second axis shows a nutrient uptake gradient. Generally, the higher pH values – in this context it means neutral pH levels – accompany the sites where the nutrient uptake is not limited by acidic pH. The positive correlation of the PAP, PAK levels and Axis 2 along with a negative relation with pH (H₂O) seems to be contradictory. The relevés affected by groundwater have lower pH values, which cause limited nutrient uptake, and the groundwater is usually richer in nutrients due to the fertilization of the adjacent arable lands. These processes can result in higher PAP, PAK or even TN levels than in relevés affected only rarely by groundwater. Species with higher nutrient needs occur on the negative end of this axis, while the positive values on this axis are accompanied by species which require lower nutrition levels. Groups of soil parameters show close relationship with the species composition of the study area, but soil physical parameters, therefore the water regime, seems to be a more fundamental factor than soil chemical characteristics (Research question 2). The larger number of relevés could result in a stronger connection between environmental and plant data.

The vegetation follows the changes in the microrelief of the sample areas (*Figure 6 and Figure 7*). Differences in elevation in these areas are small. Between the highest and lowest point of the total area the difference in elevation is only 1.4 m. Even on the fields, the vegetation follows the 10–20 cm height differences. Where the surface rises “suddenly”, the plant communities are arranged in stripes, and where the surface is nearly flat, they show a patchier arrangement. The analysis the DEM helped to make the correlation quantifiable between vegetation pattern and microtopography. Our findings support the results of Diamond et al. (2019) – as patch distribution is affected highly by the presence or by the lack of water. Some plant communities occur only in hollows and some are dry tolerant groups that were found on hummocks (Research question 3). Ladányi et al. (2016) described similar allocation of plant communities in a saline wetland. Future studies may use a higher spatial resolution DEM or even terrestrial laser scanning along with spatial statistics to find more fine-scaled relations.

Thus, it can be stated that the formation of different types of associations is highly dependent on the soil conditions of the area and can be closely related to it. However, in the formation of the fine mosaic pattern (in a lowland environment) the diversity of the microrelief and the differences in the period of flooding or saturated soil conditions play a crucial role (Jager et al. 2015, Li et al. 2017, Ma et al. 2021, Diamond et al. 2019, Diamond et al. 2020).

5. CONCLUSIONS

The present study examined the correlations between the characteristic soil types of the Hanság and Tóköz and the grassland plant associations that have developed on them. The soil classes of the sample areas and the physical and chemical properties of the topsoil were determined using laboratory tests. The plant associations of the areas and the microrelief categories produced from surface models showed close relationship. The patches of the

vegetation maps coincided with the hummock and hollows categories. The results of the plant association analysis were compared with the results of soil characteristics. We found that soil type determined the predominant vegetation type on a habitat level, but it is not responsible for the mosaic pattern formed by the associations. The distribution of the dominant species of the plant groups were closely determined by groups of soil parameters according to the CCA. We also found that the microrelief changes, and therefore the length of the saturated or flooded soil conditions, can be the reason behind the mosaic pattern of the vegetation pattern. According to our results, the vegetation follows the changes in the microtopography adequately, and it also indicates the minimal (10–20 cm) deviations reliably. Future studies should consider using more environmental parameters such as precipitation and groundwater fluctuation in multiple analyses.

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Mapping Forest Cover Changes using Sentinel-2A Imagery in the Municipality of Zubin Potok, Republic of Kosovo

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Abstract – This research aimed to investigate the changes in forest cover, utilizing Sentinel-2A imagery data. Annual results of deforestation, non-forest, and forest area in the Municipality of Zubin Potok (Kosovo) between 2016 and 2017 were presented and analyzed by applying the image difference change detection method on a Normalized Difference Vegetation Index (NDVI) product derived for both years. The study reveals that forest coverage in this municipality has changed due to human activity (harvested and burnt forests). The footprint of changes was evidenced by using Sentinel 2A band combinations and very high resolution (VHR) images available in Google Earth (GE). From the overall forest-covered area of 24,873.61 hectares, the detected changes during the annual period are as follows: 24,423.57 ha or 98.19 % is mapped as forest, 113.75 hectares or 0.46 % as non-forest, and 336.77 or 1.35 % of the area forest is mapped as deforestation. These results can be used to identify human-made deforestation and to develop monitoring forest plans for the coming years.

deforestation / reforestation / vegetation indexes / change detection / sample design / accuracy assessment

Kivonat – Az erdőterület-változása Sentinel-2A űrfelvételek alapján Zubin Potok község határában, Koszovóban. A tanulmány Sentinel-2A műholdfelvételek alapján egy erdősült terület változását vizsgálja. Az erdőterület éves változását 2016 és 2017 között Zubin Potok (Koszovó) községhatárában mutatja be és elemzi a felvételek vegetációs index (NDVI) alapú változása alapján. A tanulmány megállapítja az emberi tevékenység (fakivágás) és az erdőtűz okozta területváltozásokat a községhatárban. A változásokat a Sentinel-2A űrfelvétel és a Google Earth (GE) felvételek egyértelművé teszik. A teljes 24 873,61 hektáros erdőterületből az éves időszakban észlelt változások a következők: 24 423,57 ha vagy 98,19 % erdőként, 113,75 hektár vagy 0,46 % nem erdőként és 336,77 vagy 1,35 % -a az erdőt erdőirtásként ábrázolják. Ezek az eredmények felhasználhatók az ember által okozott erdőirtások azonosítására és a következő évekre vonatkozó erdőterv kidolgozására.

erdőirtás / erdőfelújítás / vegetációs indexek / változás vizsgálata / mintavétel kialakítása / pontosság-vizsgálat

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1 INTRODUCTION

Recently, the increased amount of imagery data coming from remote sensing technology empowered the science community and beyond to study and research important aspects of land cover and use changes on the living environment. Information on land cover and land use change inventory are essential data for different environmental issue implementations such as; deforestation, estimated devastations, disaster observations, urban growth, land management, and land planning (Hussain et al. 2013). According to Achard et al. 2009, INPE 2014, FAO, JRC, SDSU, and UCL 2009 as cited in (Hojas-Gascón et al. 2015) “for more than a decade the monitoring of deforestation has successfully been carried out at regional levels using medium-spatial resolution satellite data, predominantly from the Landsat sensor, which has 30 m spatial resolution and a revisit frequency of 16 days”. In 1997, the World Resources Institute (WRI) founded the Global Forest Watch (GFW) as an initiative for forest frontiers, reporting only on a few pilot countries at the beginning until growing as an online global platform that provides data and tools for anyone to enter and obtain information on how and where forest cover is changing (WRI 2019).

Another valuable online inventory of the land cover product is Copernicus – the European Union’s Earth Observation Programme, served by imagery data from the Sentinel satellite family. The Copernicus Land Monitoring Service (CLMS) delivers spatial information on land cover use and its changes, vegetation, and other products in the field of environmental land applications to a wide array of clients in Europe and across the world (EEA 2018).

Various image transformation indexes among spectral bands of various satellite sensors have been created for monitoring vegetation status on a continental and global scale including the most broadly applied Normalized Difference Vegetation Index (NDVI) using the Advanced Very High Resolution Radiometer (AVHRR) sensor on board the NOAA series of satellites (CCRS 2019) and Moderate Resolution Imagine Spectroradiometer (MODIS) sensors on the Terra and Aqua satellites. These both have high temporal resolution (one day revisit time) and their reflectance data are convenient for time series vegetation dynamic analysis at regional and global scales. However, due to their very coarse spatial resolution of 1 km (AVHRR) and 250 m (MODIS), the investigation of phenological dynamics is problematic for finer or local scale vegetation status monitoring (Walker et al. 2012).

Furthermore, Landsat series of satellites provides the longest and richest archive (over 40 years) of systematically collected remotely sensed data (Goward et al. 2006) with valuable information and possibilities for enhanced knowledge of methods and extents of past forest changes and recovery (Banskota et al. 2014). In addition, a 30 m spatial resolution and 16-day repetitive temporal resolution makes Landsat data well suited for land cover monitoring of the Earth’s surface (Gillanders et al. 2008). Concerning the diverse possibility of remotely sensed data from both optical and radar sensors, monitoring an environmental phenomenon employing temporal and spatial resolutions of the data is reduced to five days and higher spatial resolution to 10 m with the launch of the Sentinel-2 mission by ESA in June 2015. In remote sensing (RS) technology, the common intention of the change detection approach is to point out the geographic position of land cover changes, change calculation, and map result validation (Coppin et al. 2004, Im - Jensen 2005, Macleod - Congalton 1998).

The Normalized Difference Vegetation Index (NDVI) is a widely used vegetation index because it is useful in remotely sensed data calculation (Huete – Liu 1994) and strongly revealed global vegetation cover monitoring in the past two decades (Leprieur et al. 2000). According to Singh (1989), change detection is “the process of identifying differences in the state of an object or phenomenon by observing it at different times”. Brothers and Fish as well as Malila and Singh, as cited (Macleod – Congalton 1998), reported: “four aspects of change

detection are important when monitoring natural resources: (1) detecting that changes have occurred, (2) identifying the nature of the change, (3) measuring the areal extent of the change, and (4) assessing the spatial pattern of the change". For improved understanding, the change detection method types are grouped into seven categories: 1. algebra, 2. transformation, 3. classification, 4. advanced models, 5. Geographical Information System GIS approaches 6. visual analysis, and 7. other approaches (Lu et al. 2004b). The change detection technique is one of the key implementations in remote sensing (RS), moreover using bi-temporal or multi-temporal data imagery (Campbell – Wynne 2011). According to Singh (1989, p. 990), "there are two basic approaches for change detection; (1) comparative analysis of independently produced classification for different dates and (2) simultaneous analysis of multi-temporal data". The image difference technique requires two accurately co-registered image data sets in order to generate a new subtracted image, the values of which indicate the changes (Hussain et al. 2013). Although different change detection techniques are currently available, they are difficult and require choosing an appropriate algorithm to achieve change detection results practically (Lu et al. 2004). Therefore, defining an appropriate threshold for mapping class change category is one of the most critical steps (Lu et al. 2005). The application of image thresholding in computer vision is to segment the objects based on the image pixel intensities by using a grayscale image as input and threshold, and the result is a binary image.

Checking accuracy assessment is an essential part of any project that deals with remotely sensed data. Many reasons that emphasize the significance of the accuracy assessment exist: "1) the need to know how well you are doing and to learn from your mistakes; 2) the ability to quantitatively compare methods; and 3) the ability to use the information resulting from your spatial data analysis in some decision-making process" (Congalton 2001, p. 321).

An error matrix table successfully describes a precise classification map by containing commission and omission mistakes. A commission error indicates the pixels or areas are wrongly assigned to that map category, while an omission error represents the pixels or areas correctly assigned to that map category (Congalton – Green 2009). Use of the error matrix table is also possible to calculate other measures of classification change validation such as overall accuracy as well as produce and user accuracy (Story – Congalton 1986).

The existing literature on the status of forest monitoring using remotely sensed data is quite applicable. Deforestation and reforestation are common environmental topics across the world. The direct human cause of forest land transformation to a non-forested land was defined as deforestation and the transformation of non-forest land (which was previously covered under forests) into the human-induced forest through the planting of seedlings, or the planting of natural seeds is defined as reforestation (UNFCCC 2002).

Based on the National Forest Inventory Kosovo 2012 Report (Tomter et al. 2013), forests cover an area of 481,000 hectares or 44.7 % of the total country land area, which is dominated by deciduous forest (93 %), coniferous forest (5 %), and mixed forest (2 %). Concerning the status of Kosovo loggings, according to this report, the annual permitted logging level allowed is about 1.4 million m³. This level was exceeded by an estimated 1.6 million m³ of annual loggings. In addition, 7% of loggings were conducted according to forest legislation and around 12,200 hectares, or 2.5 % of the total forest areas, were severely burned. The data analyzed from this report constitute the reason for increased study of the state of forests in Kosovo. Therefore, we have decided to investigate the forest changes in a one-year difference (2017-2016) in this study area and address the following research objectives: How can deforestation be detected and mapped? How can non-forested areas that have been previously deforested be detected and mapped? Is there any human intervention involved in the reforestation?

2 MATERIALS AND METHODS

2.1 Study area

Defining the study area was one of the research challenges. The forest area examined for this study is located in the municipality of Zubin Potok in the northern part of the Republic of Kosovo, located between the latitudes $42^{\circ} 48.507'N$ and $43^{\circ} 2.120'N$ and longitudes $20^{\circ} 29.076'E$ and $20^{\circ} 47.839'E$. The area extends over 333 km^2 and has a population of 6,616 (KSA 2013). In its southern part, this municipality borders Istog and Skënderaj, while in its eastern part it borders Zvečan. Its entire western part borders Serbia (Figure 1). The area is characterized by mainly mountainous relief and scattered settlements. Its main economic branch is agriculture. The area is also home to an artificial accumulation of the lake of Ujman (Gazivoda). In addition to being of great importance for the municipality and the country, the lake is one of the largest artificial lakes in Kosovo with an extended surface of 9 km^2 .

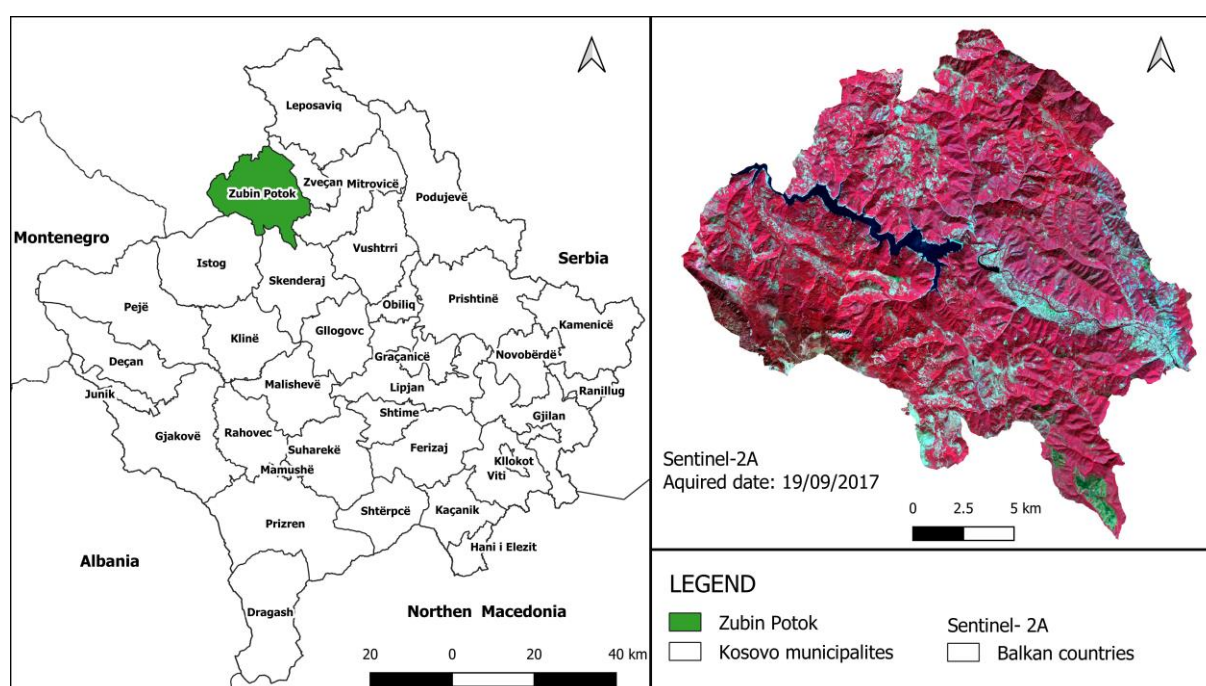


Figure 1. The geographical location of the study area in Kosovo (left), and Sentinel 2A color composite map (right). The map to the right of Figure 1 used in this study is a color composite image of these bands combination: NIR, RED, and GREEN. The red color on the map indicates forest vegetation; the green color represents deforestation, the blue color represents the water surface, the cyan, and other colors represent the surfaces not covered with forests (settlements, roads, bare land, agricultural areas, etc.).

According to CLC (CORINE Land Cover), 2018 inventory (EEA, 2018), 24,850.32 hectares (77.43 %) of the total area of the municipality – 33,385.6 ha (100 %) – is forest covered (deciduous, coniferous, and mixed), 3,207.28 ha (9.61 %) is semi-forested (meadows and shrubs), 4,133.42 hectares (12.38 %) are agricultural, 774.21 ha (2.32 %) waters (lakes and rivers), and 129.32 ha (0.39 %) of the surface is a built-up area.

2.2 Imagery Data and their Processing

The multi-spectral imagery data set of Sentinel satellite platforms 2A has been used as a primary source. Two cloud-free images were selected from 15/08/2016 and 19/09/2017 and

downloaded from the Copernicus Data and Information Access Services (DIAS) via the Mundi web services platform (<https://mundiwebservices.com/>). Sentinel-2A satellite has 13 spectral bands from visible through near-infrared to shortwave infrared: four image bands at 10 m, six bands at 20 m, and three other bands at 60 m spatial resolution (ESA 2015).

Table 1. The spatial and spectral resolution of Sentinel 2-A bands

Band number	Band name	Spatial resolution (m)	Central wavelength (nm)	Bandwidth (nm)
2	Blue	10	492.4	98
3	Green		559.8	45
4	Red		664.6	38
8	NIR		832.8	145
5	Vegetation Red Edge (VRE)	20	704.1	19
6	Vegetation Red Edge (VRE)		740.5	18
7	Vegetation Red Edge (VRE)		782.8	28
8a	Vegetation Red Edge (VRE)		864.7	33
11	SWIR	60	1613.7	143
12	SWIR		2202.4	242
1	SWIR		442.7	27
9	SWIR		945.1	26
10	SWIR		1373.5	75

Source: (<https://earth.esa.int/web/sentinel/user-guides/sentinel-2-msi/resolutions/radiometric>)

The Sentinel-2 mission is a constellation of two satellites (Sentinel-2A and Sentinel-2B) that provide high-resolution optical imagery on global coverage of Earth's land surface. Every ten days it revisits every single satellite and every five days with the combined constellation of the second satellite, making the data of great use for land monitoring studies (Addabbo et al. 2016).

Processing Level-1C and Level-2A of MSI Sentinel 2A products are freely available to users. The Level-2A processing of MSI Sentinel-2A data contains a Scene Classification and an Atmospheric Correction applied to Top-Of-Atmosphere (TOA) Level 1C orthoimage products (ESA 2015). The main output is an orthoimage Bottom-of-Atmosphere (BOA) corrected reflectance product, resampled and generated with an equal spatial resolution for all bands, and it can be used at the request of users in three levels of spatial resolution: 10 m, 20 m, and 60 m (ESA 2015). The metadata of Sentinel-2A, such as a product item, spacecraft name, processing level, product type delivered, and the date of acquired imageries is described in *Table 2*.

Table 2. Main metadata of the selected Sentinel-2A imageries

Product	Spacecraft name	Processing level	Acquisition time
S2A_MSIL2A_20160815T093042_S0100_R136_T34TDN_20160815T093218	Sentinel – 2A	Level-2A	2016-08-15
S2A_MSIL2A_20170919T093031_N0205_R136_T34TDN_20170919T093732	Sentinel – 2A	Level-2A	2017-09-19

2.3 Methodology

To complete the research objective, the following methodology was applied. A 10 m spatial resolution of Level-2A of MSI Sentinel-2A spectral bands: 2 (Blue), 3 (Green), 4 (Red), and 8 (NIR) covering the study area downloaded. Spatial and spectral subset and layer stacking of an orthoimage Sentinel-2A corrected reflectance images was realized by the raster tool in QGIS. The Sentinel-2A bands 4 (RED) and band 8 (NIR) that belong to the visible and near-infrared (VNIR) electromagnetic spectrum were selected for further use. NDVI₂₀₁₆ and NDVI₂₀₁₇ maps creation is the main step to proceed further with change detection analysis. NDVI is calculated by dividing the surface reflectance difference between near-infrared (NIR; 0.842 μm), and visible red (R; 0.665 μm) spectral bands by their sum, given in a value between -1 and 1 (Tucker et al. 1985):

$$\text{NDVI} = (\text{NIR} - \text{R}) / (\text{NIR} + \text{R}) \quad (1)$$

To conduct change detection analysis in the forest area, the following tasks such as image difference, image threshold, and refinement of the change detection results, were undertaken by using the Image Change Workflow tool in ENVI 5.3 software. The image difference method could be performed directly on a single band image or a single transformation image. The formula to calculate the difference change image is:

$$\text{dNDVI}_{(2016-2017)} = \text{NDVI}_{2016} - \text{NDVI}_{2017} \quad (2)$$

An image difference algorithm was applied by subtracting NDVI₂₀₁₆ from NDVI₂₀₁₇, to create a difference NDVI (dNDVI₂₀₁₆₋₂₀₁₇) map. To detect and map the changes in the forest area, Otsu's threshold algorithm by auto-default settings is applied on the dNDVI₍₂₀₁₆₋₂₀₁₇₎ grayscale image. Otsu (1979) introduced the discriminant criterion η as a ratio between-class variance and total variance (total = between-class + within-class variance). He proved that the optimal threshold k maximizes the ratio η or equivalently maximizes the between-class variance. The equation below describes the calculation of the threshold using two options: Within class variance:

$$\sigma_{\omega}^2(t) = \omega_0(t)\sigma_0^2(t) + \omega_1(t)\sigma_1^2(t) \quad (3)$$

Where ω_0 and ω_1 are the probabilities of the two clusters separated by a threshold (t), σ_0^2 and σ_1^2 are the class variances. From the L bins of the histogram is computed the class probability $\omega_{0,1}(t)$:

$$\omega_0(t) = \sum_{i=0}^{t-1} p(i) \quad (4)$$

$$\omega_1(t) = \sum_{i=t}^{L-1} p(i) \quad (5)$$

Between class variance:

$$\sigma_b^2(t) = \omega_0(t)\omega_1(t)[\mu_0(t) - \mu_1(t)]^2 \quad (6)$$

Where, ω express class probabilities; μ express class means. The class means $\mu_0(t)$, $\mu_1(t)$ and μ_T are computed:

$$\mu_0(t) = \frac{\sum_{i=1}^{t-1} ip(i)}{\omega_0(t)} \quad (7)$$

$$\mu_1(t) = \frac{\sum_{i=1}^{L-1} ip(i)}{\omega_1(t)} \quad (8)$$

$$\mu_T = \sum_{i=t}^{L-1} ip(i) \quad (9)$$

There is a possibility that all the following relations can be easily verified:

$$\begin{aligned} \omega_0\mu_0 + \omega_1\mu_1 &= \mu_T \\ \omega_0 + \omega_1 &= 1 \end{aligned} \quad (10)$$

Repetitively the calculation of class means and class probabilities can be done. This brings an effective algorithm:

1. Compute the histogram and intensity level probabilities
2. Initialize $\omega_1(0)$ and $\mu_1(0)$
3. Iterate through all possible thresholds: $t = 1, \dots$ max. intensity
 - 3.1. Update ω_1 and μ_1
 - 3.2. Compute $\sigma_b^2(t)$
4. The max. $\sigma_b^2(t)$ value is the final threshold.

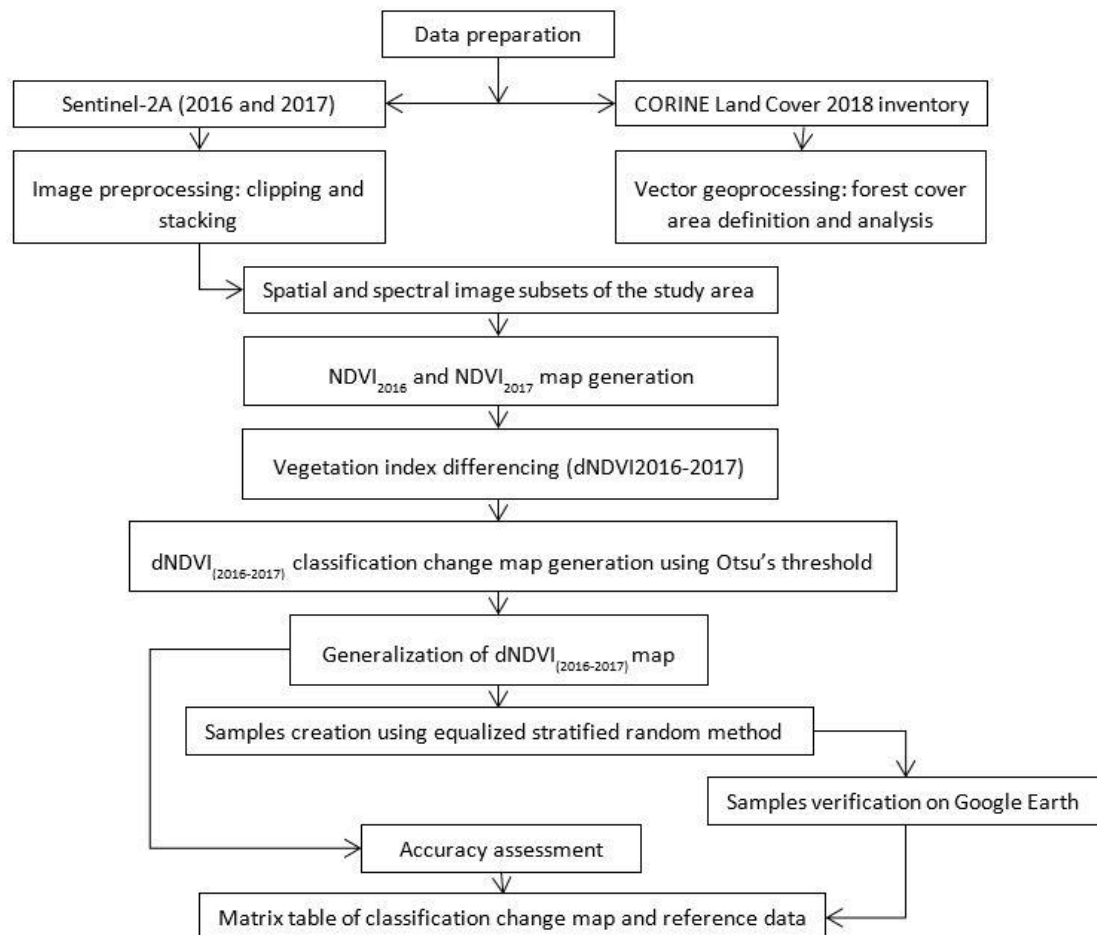


Figure 2. Flowchart depicting the working methodology in this research

3 RESULTS AND ANALYSIS

This paper analyzed forest cover changes in the Municipality of Zubin Potok from 2016 to 2017 by utilizing the vegetation index difference method of change detection algebra technique on the Sentinel-2A imagery data. Result interpretation is described in the following chapters.

3.1 NDVI maps

In this study, the RED (4) and NIR (8) bands of the Sentinel- 2A at 10m spatial resolution were used to generate $NDVI_{2016}$ and $NDVI_{2017}$ maps using the NDVI equation (1). In practice, water bodies, bare ground, artificial features, and other non-vegetative areas correspond below 0.1 NDVI values; and higher values indicate a higher photosynthetic activity such as shrubs, grasslands, crops, temperate, and tropical forest (Meneses-Tovar 2011/12).

Table 3. Normalized difference vegetation indexes ($NDVI_{2016}$ and $NDVI_{2017}$) basic statistics

Statistics	NDVI 2016	NDVI 2017
Minimum	-0.98	-0.88
Mean	0.86	0.84
StdDev	0.08	0.11
Maximum	0.99	1.00

Table 3 presents the basic statistics of $NDVI_{2016}$ and $NDVI_{2017}$ maps, such as minimum, mean, standard deviation, and maximum.

Figure 3 presents the $NDVI_{2016}$ and $NDVI_{2017}$ maps, and their values indicate the spatial distribution differences of forest cover between years. The color ramp from yellowish to reddish of the $NDVI_{2017}$ map in the southeastern part of the study indicates the area with negative values or no vegetation due to fires or forest cutting by human activity. However, more detailed interpretations of the NDVI maps will be explained by applying the vegetation index difference method.

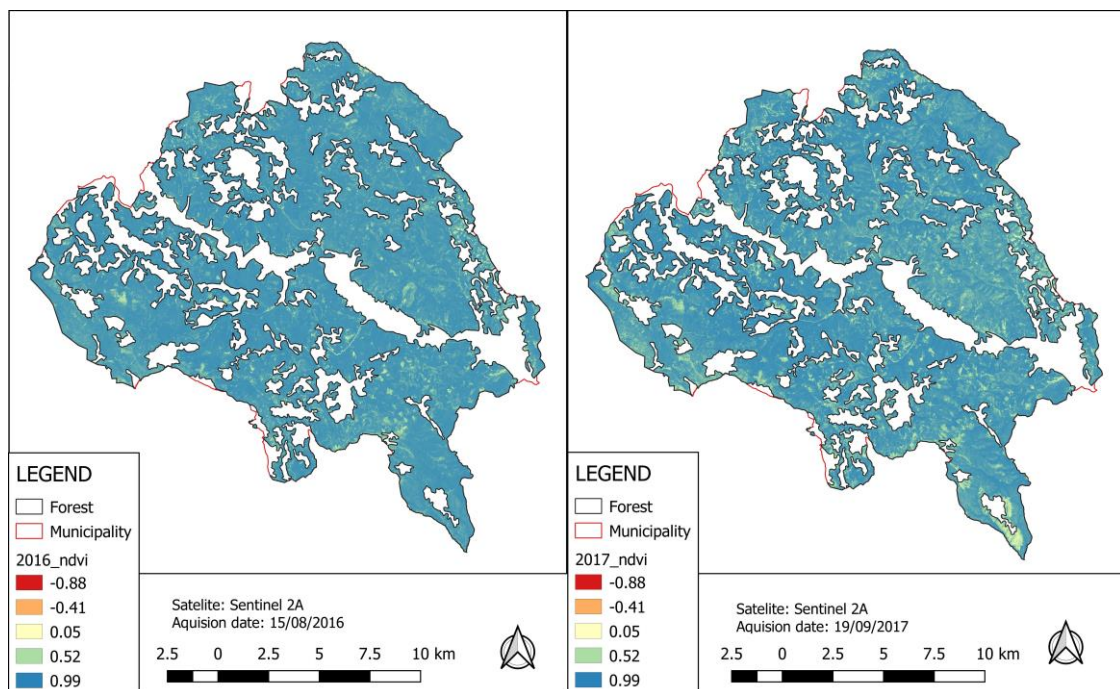


Figure 3. The Normalized difference vegetation indexes - $NDVI_{2016}$ (left) and $NDVI_{2017}$ maps (right) of the study area

3.2 Difference NDVI maps

By applying the image difference method on NDVI pairs, the result is the image difference NDVI output. The color ramp of the difference image $dNDVI_{2016-2017}$ map presented in *Figure 5* reveals the different intensity of pixels which indicate the differences in vegetation condition between annual years, either forest loss or forest growth. The histogram of the newly created difference image has both negative and positive pixel values. Pixels with negative and positive values indicate the changing area by scattering on the edges of the distribution curve (Singh 1989) when pixels with zero or close to zero values indicate unchanged by scattering around the zero (Lu et al. 2005). *Figure 4* shows the distribution curve of difference image $dNDVI_{(2016-2017)}$, while table 4 shows the basic statistics of difference $dNDVI_{(2016-2017)}$.

Table 4. Difference of $NDVI_{2016}$ and $NDVI_{2017}$ basic statistics

Minimum	Mean	StdDev	Maximum
-0.84	-0.01	0.05	1.02

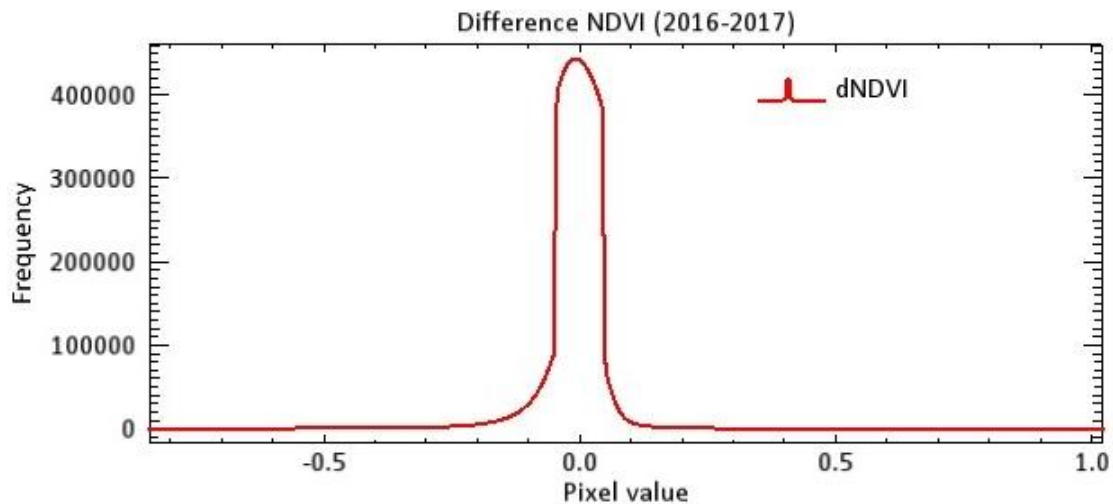


Figure 4. Histogram of $dNDVI_{(2016-2017)}$ map

3.3 Change classification map

The left map in *Figure 5* shows the spatial distribution of the $dNDVI_{(2016-2017)}$, and the map on the right of the figure determines the classification change forest in this study by selecting Otsu's automatic threshold. Of the three categories classes mapped inside the forest area, the forest class indicates the non-changed forest areas, the non-forest shows the previously deforested areas, and the deforestation class indicates cut-out forest areas between the years.

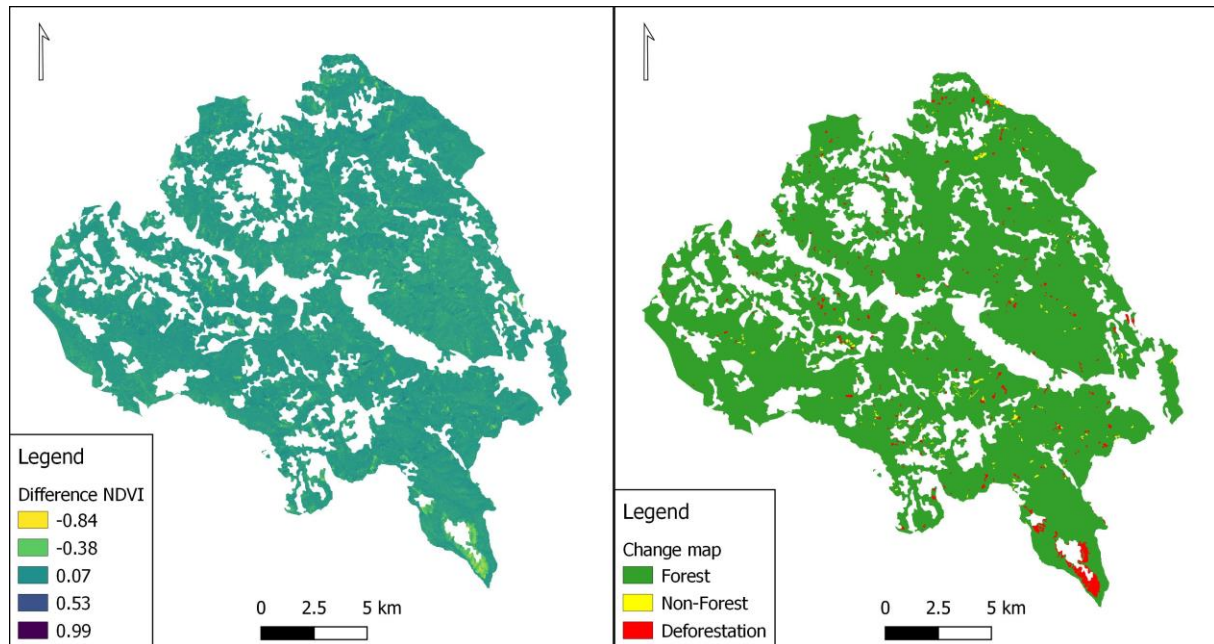


Figure 5. Difference $NDVI_{(2016-2017)}$ map (left) and classification change map (right)

Table 5 shows the distribution of these three classes. Forest class covers the most class area with 98.19%, the non-forest class has the least with 0.46%, and deforestation class covers 1.35% of the total area and represents clear-cutting forest activity. Also, the description of the sampling size for each category class is included in this table.

Table 5. Map category and sample size statistics

Class name	Classification statistics		Sample size	
	Area (ha)	Percent (%)	Number per class	Total (%)
Forest	24423.57	98.19	50	33.33
Non-Forest	113.27	0.46	50	33.33
Deforestation	336.77	1.35	50	33.33
Total	24873.61	100.00	150	100

3.4 Sampling sites and verification

Without the possibility of verifying field classification samples, time series of very high resolution (VHR) images on the Google Earth platform were utilized. All the category class samples (150) were covered with images in Google Earth and verified in the periods before and after the detection of forest cover changes (August 2016 - September 2017). In Figure 6, the yellow polygons represent the areas covered with forests in 2016, while the polygons in Figure 7 visually show the temporary removal of forest cover due to clear-cut. In Figure 8, the yellow polygons in the vast majority show the areas not covered with forests in 2016 that were deforested previously. On the other hand, in Figure 9, the yellow polygons clearly indicate that no artificial reforestation activities have occurred.

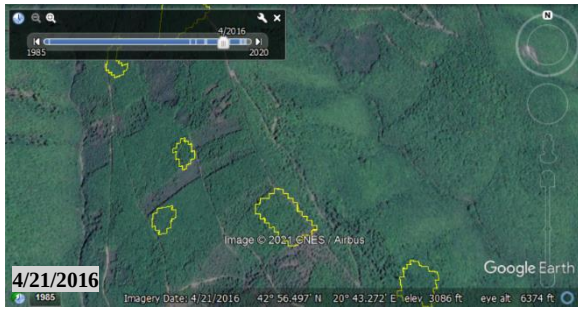


Figure 6. Yellow polygons indicate the forested area in 2016, visualized in GE

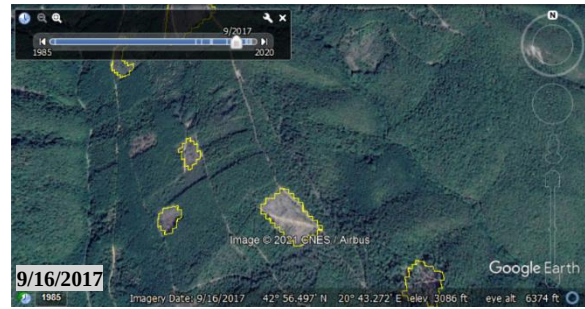


Figure 7. The clear-cut forested areas in 2017, interpreted and verified in GE



Figure 8. Example of the non-forested areas detected in 2016



Figure 9. The yellow polygons of non-forested areas in 2017 shows no human reforestation

3.5 Validation of classification change

Quantitative accuracy assessment was utilized using the error (confusion) matrix in ENVI 5.3 software. Table 6 presents the error matrix of the reference data and classification change in percentage and number of pixels of the study area. From 50 samples of deforestation area, reference data shows that 40 belong to the deforestation class, eight to non-forest, and one of them remain in the forest class. From 50 samples of non-forest areas, eight were placed incorrectly in the deforestation class and none in the forest class. Only one sample site of the forest class belongs to the deforestation class.

Table 6. Error matrix table of reference data and classification change

		Reference data pixel and (percent)			
Classification pixel and (percent)	Class name	Forest	Non-Forest	Deforestation	Total
	Forest	49 (94.23)	0 (0.00)	1 (2.04)	50 (33.33)
	Non-Forest	0 (0.00)	42 (85.71)	8 (16.33)	50 (33.33)
	Deforestation	3 (5.77)	7 (14.29)	40 (81.63)	50 (33.33)
	Total	52 (100.00)	49 (100.00)	49 (100.00)	150 (100.00)

The overall accuracy of classification change is calculated by dividing the total sum of diagonal correctly classified pixels (131) by the total number of reference points (150). The compounded overall accuracy was 87.33%. Producer accuracy is calculated by dividing each

diagonal pixel value class by the total of each column. *Table 7* shows that the highest producer's accuracy possesses forest area (94.23 %), then the non-forest areas ranges to (85.71 %), and the least have deforestation area around 81.63 %. User accuracy is calculated by dividing each of the diagonal pixel value classes by the total of each row. From the results of *Table 6*, the forest area has the highest user accuracy (98.00), followed by non-forest (84.00 %), and deforestation (80.00 %).

Table 7. Validation measurements of classification change

Class name	Commission error (%)	User accuracy (%)	Omission error (%)	Producer accuracy (%)
Forest	2.00	98.00	5.77	94.23
Non-Forest	16.00	84.00	14.29	85.71
Deforestation	20.00	80.00	18.37	81.63

4 DISCUSSION AND CONCLUSIONS

Acquiring spatial information on vegetation status using geospatial technologies has become necessary for sustainable forest management. In this research, we used medium-spatial resolution satellite imagery of the Sentinel 2-A platform to detect and map the deforestation process between 2016 and 2017 within the forest area. The image difference method is easy to apply to conduct a grayscale image by subtracted vegetation indices (VIs) of two dates NDVI, but it is difficult to manually setup the appropriate thresholds. The application of the Otsu's threshold on the image differenced NDVI monochrome image (NDVI₍₂₀₁₆₋₂₀₁₇₎) enabled us to detect and map the deforested and non-deforested areas that were previously under forest. The results of accuracy assessment show that this approach is acceptable (overall accuracy was 87.33%). Researchers have used different forest classification approaches, change detection methods, and algorithms to evaluate the forest cover change process. They have also utilised multi-spectral images and VIs. The VIs of the NDVI, enhanced vegetation index (EVI), and leaf area index (LAI) had derived from multi-spectral images used by Elhag et al. (2021) for mapping spatial-temporal land cover distribution, mapping bare soil index (BSI), and in identifying the significant land cover changes over 20 years (1995-2015) in the Sougia catchment of Crete Island, Greece. The VIs of NDVI was derived from Landsat data, EVI was derived from MODIS time-series and used as an optimized index, and LAI as NDVI derivatives to define up to ten land cover classes. The supervised image classification method using Support Vector Machine (SCM) train algorithm was applied to create land cover maps for three periods: 1995, 2005, and 2015 and to assess the classification accuracy. Their results compared with CLC categories map as ground truth data. The overall accuracy of the SVM classification algorithm was over 87.00 % in three periods. As a change detection method, Elhag et al. (2021) used a post-classification comparison between the spanning times and revealed a significant depletion of -14% in the coniferous forest from 1995 to 2015. Nath and Acharjee (2013) used the NDVI index to generate maps by slicing five ranges of NDVI applying the Jenks Natural Breaks classification method in their study area. The final step in their research was the creation of the vegetation cover change map, where NDVI categories map (decreased, some decreased, some increase, and increased) of 1989 and 2010 had crossed and revealed significant changes. From the total area (2893.59) hectares, reduced class shows 44.40%, followed by some decrease 37.93% and remaining falls under some increase and increasing trend. Candra (2020) has developed a method to detect deforestation in his work in Kalimantan and Sumatera (Indonesia) using multitemporal satellite imagery from 2018-2019.

He called this method Multitemporal Deforestation Detection (MDD). The main idea was to determine the difference between the reflection values in the targeted image (image that has deforested pixels) and in the original one (image without change of forest pixels). To develop this algorithm, Candra took two main steps: a) Band selection – several pixels representing the deforestation from the target and original image are taken, and the change in their reflection values is calculated. The bands that have the most significant changes in values from the results are selected and the threshold is also selected by performing some observations. b) With the created algorithm, the combination is made using NDVI and difference normalized burn ratio (dNBR) - to increase the accuracy of the results. The commission error results of deforestation detection were a total of 0.63%, while, on the other hand, the omission error is 0.33%. Given that the errors are small, this then provides the user accuracy and producer accuracy higher accuracy. Concerning our study, the selection of Equalized Stratified Random sampling strategy samples for classification verification has reduced the overestimation of the classification result, especially for the forest and non-forest class, which were the target of the classification. As the verification process of the samples relayed only VHR Google Earth images, field verification seems necessary in future research, especially to check the regeneration process at the early stage, which is not visible from satellite images. The difficulty during this study was that the work was based solely on using Remote Sensing and GIS desktop software, making it impossible to directly access platforms that offer real-time data for spatial analysis and change detection.

Therefore, in the future, such research would be easier and more resource intensive using modern web-based platforms such as Google Earth Engine (GEE), which provides high-speed data analysis for large spatial extents using processing function and provide algorithms to gather data from multiple years, satellite sensors and models (Zurqani et al. 2018). The results of the image difference method applied in this study revealed that forest cover in this municipality has changed both from human (forest cutting) and natural factors (forest fire). Based on the Kosovo Green Report 2018 (Report, 2018), during 2017, around 2.040 m³ of timber was confiscated from illegal loggers by communal authorities and 2.054 ha forests experienced fires in Kosovo. Illegal forest cutting is much related to the poor social and economic situation, especially in poor rural areas where forest resources are utilized for survival. From the overall forest-covered of 24,873.61 hectares, 24,423.57 ha or 98.19 % mapped as forest cover, 113.75 hectares or 0.46 % as non-forest, and 336.77 or 1.35 % of the area forest mapped as deforestation. The percentage of deforestation area is worthy of attention, and in the future, we intend to investigate spatial-temporal forest cover changes till to present time.

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Tissue Proportion, Fibre, and Vessel Characteristics of Young *Eucalyptus* Hybrid Grown as Exotic Hardwood for Wood Utilization

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Abstract – This study sought to determine selected anatomical properties of young *Eucalyptus* hybrid species (*E. grandis* × *E. urophylla*) grown in Ghana. Images of fibres from macerated wood, and micro-sections produced with microtome were analysed using a compound digital microscope associated with Motic Image Plus Software (MIPS), version 2.0, installed on a computer. Images were initially processed using ImageJ software. Study data were analysed using an R statistical package. The overall mean value for fibre length was 907.67 µm, whereas double fibre wall thickness was 7.76 µm. Both variables had higher mean values in sapwood than in heartwood. Nevertheless, the found values decreased from the butt to the top portion. Statistically, axial and radial positions had no influence on fibre characteristics. In a 1 mm² of the cross-section, the proportion of fibres was 38%, vessels were 19%, axial parenchyma were 22%, and radial parenchyma were 21% on average. Again, the radial and axial positions had no statistical influence on tissue proportion traits for the young eucalyptus wood. Mean value for vessel area was 9462.04 µm², whereas vessel frequency per mm² was about 14. Vessels were significantly larger in area (range 9982.50 – 13544.41 µm²), yet reduced in frequency (range 6 – 17 per mm²) for sapwood. In heartwood, vessel area was comparatively smaller (range 6321.15 – 7816.69 µm²), whereas their frequency was high (range 15 – 18 vessels per mm²). Axial and radial position had statistical influence on vessel frequency and area for the young *Eucalyptus* grown in a plantation in Ghana.

***Eucalyptus* / hybrid / fibre / tissue / parenchyma / vessel**

Kivonat – Fahasznosítás céljából termesztett *Eucalyptus* hibrid fajok fiatal egyedeinek szöveti szerkezete, rost- és edényjellemzői. Ez a cikk a Ghánában termesztett *Eucalyptus* hibrid fajok (*E. grandis* × *E. urophylla*) fiatal egyedeinek egyes anatómiai tulajdonságait írja le. A macerációval elkülönített farostok fotóit, ill. mikrotómmal készített anatómiai metszetek mikroszkopikus részleteit elemeztük egy összetett digitális mikroszkóppal, amely a számítógépre telepített Motic Image Plus Software (MIPS) 2.0 verziójához kapcsolódott. A képeket eredetileg ImageJ szoftverrel dolgoztuk fel. A nyert adatokat R statisztikai szoftvercsomag segítségével elemeztük. A rosthossz átlagértéke 907,67 µm, míg a kettős sejtfalfalvastagság 7,76 µm volt. Megállapítottuk, hogy a szíjács hosszabb farostokat

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tartalmaz, melyeknek kettős falvastagsága is nagyobb a gesztben mért értékekhez viszonyítva, ugyanakkor a különbségek statisztikailag nem szignifikánsak. Az említett értékek a tő felől a csúcs irányában csökkenő értékeket mutattak, de statisztikailag nem volt igazolható az eltérés. Statisztikailag tehát az axiális és radiális helyzetek nem befolyásolták a farostok jellemzőit. 1 mm² keresztmetszetet vizsgálva a farostok aránya 38%, az edényeké 19%, az axiális parenchimáké 22%, míg a bélsugár parenchimáké 21%. A radiális és axiális helyzetnek nincs statisztikai hatása a fiatal eukaliptusz faegyedekben a vizsgált sejttípusok arányára. Az edényterület átlagos értéke 9462,04 µm² volt, míg az edények darabszáma 14 körüli érték volt 1 mm²-re vetítve. A szijácsban az edények területe a 9982,50 – 13544,41 µm² tartományban, mozgott, de darabszámuk kisebb volt a geszthez viszonyítva (6 – 17 db/mm²). A gesztben az edények területe kisebb értéket adott (6321,15 – 7816,69 µm²), míg darabszámuk nagyobb volt (15 – 18 db/mm²). Vizsgálatainkkal megállapítottuk, hogy a ghánai ültetvényen termesztett fiatal *Eucalyptus* egyedek esetén az axiális és a radiális helyzet statisztikailag befolyásolta az edények mennyiségét (számát) és méretét (területét).

Eukaliptusz / hibrid / farost / szöveti szerkezet / parenchyma / edény

1 INTRODUCTION

Wildfires, illegal logging, overexploitation to meet domestic and foreign wood demand, and other factors put continuous pressure on natural forests in tropical timber producing countries. Experts have predicted that the raw material base for wood will soon shift from natural to plantation timber. Efforts to guarantee a sustainable future supply of wood include the introduction of fast-growing exotic species like *Tectona grandis*, *Cedrela odorata*, and *Eucalyptus* species. The genus *Eucalyptus* comprises fast-growing species that are able to adapt well to marginal soils in diverse climatic conditions (Willan 1951, Woods – Peseta 1996). These characteristics make *Eucalyptus* a suitable candidate genus for commercial timber plantations that can meet the increasing wood demand as well as mitigate some alarming climate change effects. *Eucalyptus* plantations are found currently in tropical, subtropical, and temperate areas. They amount to 8% of planted forests globally (Harwood 2011).

Wood from *Eucalyptus* species are useful for pulp and paper, solid wood products, veneer, fuelwood, posts, etc. In Kenya, eucalyptus is the third most grown genus after pine and cypress. It was originally introduced in Kenya to provide biomass for powering railway steam engines (Githiomi – Kariuki 2010). Until recently, eucalyptus was only planted in small scale research plot sizes and on private lands in Ghana, primarily for shade and ornamental purposes. Admittedly, general information on original eucalyptus species has been published; however, specific research on young stems is scarce. Presently, MIRO Forestry Ghana Limited, a private organisation, has adopted a breeding technology program for *Eucalyptus grandis* and *Eucalyptus urophylla*. The goal is to create a hybrid species for an improved tree form and enhanced growth. Nonetheless, little research focusing on the wood properties has been completed on bred *Eucalyptus* species.

As is the case with other tree species, silvicultural management, age, genetics, and growing sites influence the formation and quality of the woody biomass of eucalyptus (Zobel – van Buijtenen 1989, Savidge 2003, Roque 2004). In addition, wood quality can also vary with an individual tree and between trees of same species growing under same conditions (Plomion et al. 2001, Wimmer et al. 2002, Monteoliva et al. 2005, Quilhó et al., 2006, Sharma et al. 2015).

Generally, it has been argued that timber species that are fast-growing and less than ten years old produce mostly juvenile, inferior quality wood (Zobel – Sprague 1998, Moore – Cown 2017). Accordingly, properties of young eucalyptus wood need to be investigated for efficient utilization. The anatomical structure and characteristics of wood are known to

influence the most important properties, which include density, drying characteristics, shrinkage, permeability for preservation treatment, pulp yield, paper strength, etc. (Fujiwara et al. 1991, Ofori – Brentuo 2005, Bhat et al. 2007, Yahya et al. 2010, Zanuncio et al. 2016). Moglia et al. (2008), reported that fibre and vessel length significantly varied radially within a tree, whereas tissue proportion differed considerably between trees of same species. Amidon (1981) and Barauna et al. (2014) found that vessel frequency and diameter size greatly affected papermaking properties and wood permeability. The present study aimed to establish the anatomical properties that are fundamental to enhancing the utilisation potential of hybrid *Eucalyptus* species grown in Ghana. Specific anatomical properties considered for the present study were fibre characteristics (length, diameter, lumen width, and wall thickness), tissue proportion (fibre, vessel, axial and radial parenchyma), and vessel characteristics (frequency and area). These variables could influence utilisation properties of the young wood considerably.

2 MATERIALS AND METHODS

2.1 Study site

The study was conducted with materials from a plantation site owned by MIRO Forestry Ghana Limited located near Agogo in Asante Akyem North district of the Ashanti region of Ghana (Figure 1). The land is a degraded forest reserve forming part of the forest transition zone of Ghana. Between 2013 and 2018, the district, which is located on latitude 6° 37' 5" N and longitude 1° 12' 36" W, recorded monthly rainfall between 120 mm and 150 mm. The mean temperature ranged between 26°C and 30°C (MOFA 2018). Total plot size was 50 hectares.

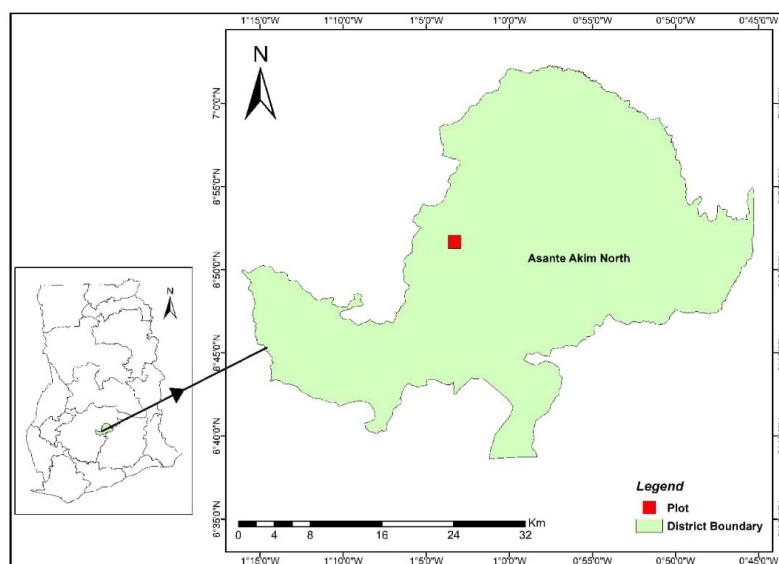


Figure 1. A map highlighting the *Eucalyptus* plot and Asante Akyem North District in the Ashanti region of Ghana.

2.2 Measurement of trees morphological features

The *Eucalyptus* hybrid (*E. grandis* and *E. urophylla*) trees were four years old, planted with 2.5 x 3m spacing, and were nurtured with MIRO's thorough silvicultural management and protection from annual wildfires. Fifty trees were randomly selected for height and diameter measurement. Diameter tape was used to measure stem diameters for the trees at breast height

position of 1.3 m. Tree heights were measured using a linear tape after the trees had been harvested close to the ground with a chainsaw. Respective stump heights were also added.

2.3 Sampling of wood materials

Six trees were randomly selected from the 50 harvested trees. MIRO donated only six trees for this destructive study. The trees were crosscut into three axial portions representing the butt, middle, and top position of tree. One 2 cm-wide wood disc was collected from the different stem height levels (butt, middle, and top) of all six trees. Eighteen (18) wood discs were labelled accordingly. Each disc was packaged in a sealed polythene and transported to the Wood Anatomy Laboratory within the Council for Scientific and Industrial Research's Forestry Research Institute of Ghana (CSIR-FORIG). The idea behind sampling from the axial position was to address any inherent variability that had naturally developed during growth of each tree. Again, there was a sharp visible distinction between sapwood and heartwood on the butt and middle discs. Therefore, one sample from heartwood and one from sapwood were taken from either side of the disc (Cherelli 2015). A total of 72 sub-samples were studied (4 sub-samples x 18 discs).

2.4 Fibre characteristics

Matchstick-sized wood pieces were taken from all sub-samples. These were placed in labelled vials and macerated using a solution of equal parts of hydrogen peroxide and glacial acetic acid. The vials containing the wood material were kept in a N53C-Genlab Oven at 60°C and monitored every 12 hours until the maceration was complete. The macerate was repeatedly washed with distilled water to guarantee total removal of acetic acid (Franklin 1945). A drop of glycerol was placed unto the macerate, and the fibres were put on a specimen slide where they were separated apart with a pin (*Figure 2*). The slides were studied under a digital Compound Microscope (National) operated alongside a Motic Image Plus software (MIPS). Images with X40 magnification (*Figure 2*) were employed for the measurement of fibre length, whereas images with X400 magnification (*Figure 3*) were used for diameter, lumen width, and wall thickness. Twenty-five (25) straight and unbroken fibres were measured for each sub-sample. This resulted in 50 fibres for sapwood and 50 fibres for heartwood, for a total of 100 fibres per disc.

2.5 Tissue proportion and vessel characteristics

Wood samples of approximately 2 cm in all dimensions were taken through a softening process following published protocols (Schweingruber 2007). After being softened, each sample was mounted on a sledge Microtome (HM 400, Microm, Walldorf, Germany) to cut microsections of about 10 – 20 µm from the cross-sectional surface (*Figure 4*). The thin sections were stained with safranin solution and further submitted to a gradual dehydration process. This was achieved by transferring the stained microsections from water through ethanol solution of 30 %, 50 %, 70 %, 90 %, and absolute ethanol. Furthermore, the sections were permanently mounted with Canada balsam and oven-dried at 60 °C (Schweingruber 2007, Tardif – Conciatori 2015). The best-mounted sections were selected, at least 3 slides per sub-sample, and studied under the microscope associated with MIPS to capture images. In ImageJ, the software scale is set using the scale of an individual image. Afterwards, a scale grid of 1 mm² was superimposed, at least 10 times, on original images representing a sub-sample. The individual tissue elements (fibre, vessel, axial parenchyma, radial parenchyma) within the 1 mm² area were counted at each placement and equated to 20.

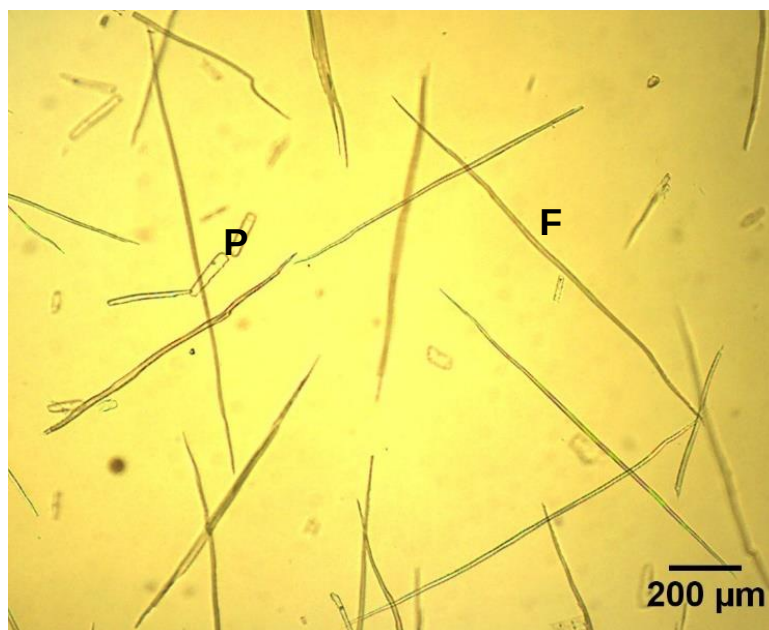


Figure 2. Fibres (F) and parenchyma cells (P) from macerated wood from 4-year-old *Eucalyptus* hybrid species grown in Ghana.

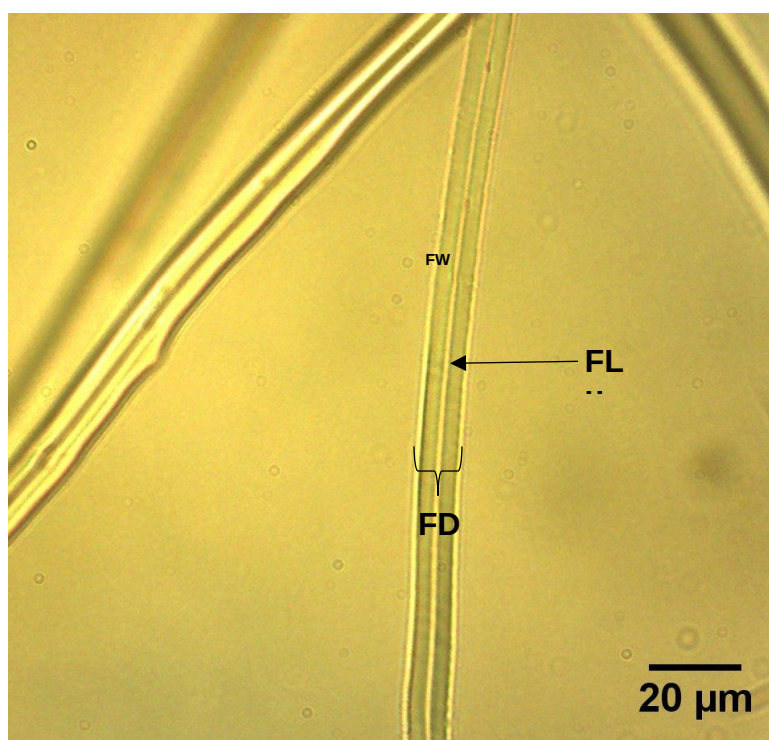


Figure 3. A magnified fibre from macerated wood from a 4-year-old *Eucalyptus* hybrid species. (FW): Fibre wall; (FD): Fibre diameter; (FL): Fibre lumen.

For instance, if vessels are 3 out of 20 spots, the proportional means are reported as percentages as $(3/20) \cdot 100$. Regarding vessel characteristics measurement, ImageJ software was used to analyse the same images captured to represent the sub-samples (Abràmoff et al. 2004). For vessel area, the images were converted into 8-bit format, inverted, and threshold set activated to convert all vessels into black dots. Using a feature called ‘analyse particle’ within ImageJ,

dot circularity was set between 0.75-1.00. Furthermore, the desired dot area was set above a pre-determined area of the smallest vessel. This excludes the many smaller dots representing cells such as axial parenchyma. Vessels were analysed as particles to estimate their area (Figures 4 and 5). A minimum of 45 vessels from three different images were feasible for area measurement for each sub-sample. Vessel frequencies were completed manually on the same-sized images.

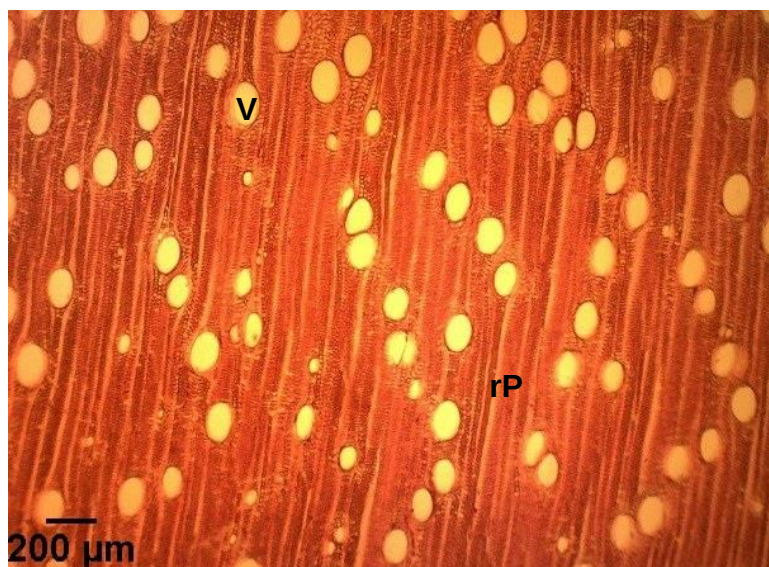


Figure 4. Cross-sectional image of wood from a 4-year-old *Eucalyptus* hybrid grown in Ghana. Image is at X40 magnification. V = vessel, rP = radial parenchyma

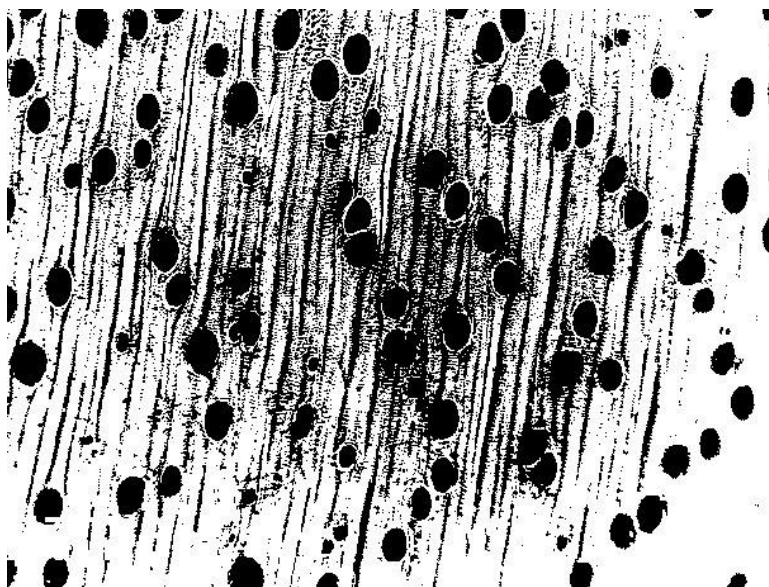


Figure 5. A processed image of a cross-section of wood from 4-year-old *Eucalyptus* hybrid species grown in Ghana. The vessels in the original image (Figure 4) are now seen as dark particles. Radial parenchyma now seen as black stripes.

2.6 Data analysis

The data generated from the study was organized with an Excel spreadsheet (Microsoft 365), and analysed using the R statistical package (Team 2014). The mean values and their corresponding standard deviations are reported in Tables 2-4. A one-way analysis of variance

(ANOVA) was employed to test if differences observed in the mean values were statistically significant. *P*-values from ANOVA outputs are included in the Tables presented above. Tukey's Honest Significant Difference was implemented to compare mean values with statistically significant differences, especially for variables with more than two categories.

3 RESULTS AND DISCUSSION

In general, the study results of morphological features, tissue proportion, fibre and vessel traits were comparable among the axial and radial positions as well as to values reported in the literature.

3.1 Morphological features

Mean merchantable height was 14.26 m, whereas the mean diameter at the butt section was 31.42 cm (*Table 1*). The mean height and diameters the present study found for eucalyptus trees grown in Ghana correspond with those reported in literature. In Brazil, Brito et al. (2019) reported a diameter at breast height (dbh) of 16.19 cm and a height of 17.07 m for clone materials of the same age. Likewise, Ramalho et al. (2019) reported a dbh range of 7.4–14.11 cm. Quilho et al. (2006) found an average dbh of 11.5 cm and an average commercial height of 17.8 m for 5-year-old *Eucalyptus urograndis* hybrid trees. The study results indicate that the hybrid eucalyptus trees have positively adapted to their growth conditions. It also suggests that *Eucalyptus* hybrid trees have sufficient crown development to provide adequate useful area for the trees (Miranda et al. 2009). The morphological findings reported in *Table 1* are important when considering the utilization of 4-year-old materials for solid wood applications such as utility poles. The impregnation of preservatives and their retention are influenced by the sapwood portion (Valle et al. 2013).

Table 1. Some morphological properties for 4-year-old Eucalyptus hybrid trees (E. grandis x E. urophylla) grown in Ghana. (Max): Maximum; (Min): Minimum; (Stdv): Standard Deviation. Total samples trees (n) = 50.

Variable	Min	Max	Mean	Stdv
Merchantable length (m)	11.55	16.87	14.26	2.20
Butt diameter (cm)	28.65	34.70	31.42	2.36
Top diameter (cm)	9.23	13.37	11.14	1.55
Sapwood width at butt (mm)	15	95	56	2.34
Sapwood width 3m from butt (mm)	37	76	53.50	1.58
Sapwood width at mid-length (mm)	40	60	47.83	0.78

3.2 Fibre biometry

The mean fibre length for the eucalyptus hybrid trees was 907 μm . The found value falls within the length range (800 to 1300 μm) reported in an earlier study and the InsideWood database (Wheeler 2011, Brito et al. 2021). Fibre length decreased from tree butt to the top portion (938.81 to 862.69 μm) as shown in *Table 2*.

The observed longitudinal variation agrees with other studies (Quilhó et al. 2006, Bhat et al. 2007). However, the abovementioned authors observed an initial increase in fibre length to about breast height before the decrease to the top portion. In the present study, the middle portion was at exactly the 50% mark of merchantable height reported in *Table 1*. Clearly, the middle portion was beyond the breast height of 1.3 m. Bamber (1985) reported a similar observation. Quilhó et al. (2006) studied eucalyptus hybrids (*E. grandis* and *E.*

urophylla) and reported 820 – 1040 μm for fibre length for trees from seed origin and 1010–1110 μm for five-and-half-year-old clones. Regarding the same hybrid grown in India, Sharma et al. (2015) reported 910–1140 μm for fibre length. Radially, the sapwood had longer mean fibre length (949.55 μm) than heartwood (862.77 μm). The differences between mean values for fibre length, for both axial and radial positions, were statistically insignificant.

Table 2. Mean values of fibre characteristics for 4-year-old eucalyptus hybrid (*E. grandis* x *E. urophylla*) grown in Ghana. (FL): Fibre Length; (FD): Fibre Diameter; (FLW): Fibre Lumen Width; (FDWT): Fibre Double Wall Thickness.

Positions	Levels	FL (μm)	FD (μm)	FLW (μm)	FDWT (μm)
Axial	Top	862.69 (81.85)	16.85 (1.82)	9.67 (1.11)	7.18 (1.07)
	Middle	923.26 (69.83)	16.49 (1.13)	8.77 (1.06)	7.72 (0.83)
	Butt	938.81 (77.86)	17.98 (1.51)	9.56 (1.33)	8.42 (1.92)
P-value		0.22	0.24	0.38	0.31
Overall mean		907.67 (40.25)	17.11 (0.78)	9.33 (0.49)	7.77 (0.62)
Radial	Heartwood	862.77 (82.86)	17.71 (1.33)	10.23 (1.50)	7.49 (1.16)
	Sapwood	949.55 (52.97)	16.49 (1.69)	8.48 (0.88)	8.00 (1.14)
P-value		0.06	0.19	0.034	0.45
Overall mean		906.16 (61.36)	17.10 (0.86)	9.36 (1.24)	7.76 (0.36)

The P-values for each variable are from a one-way ANOVA run at 95% confidence interval. In parenthesis are the standard deviation of the mean values. Total sampled trees (n) = 6.

Regarding fibre diameter (width), the mean value was 17.11 μm . This variable decreased from the butt to the middle, but slightly increased from the middle to the top portion (Table 2). The study finding on fibre diameter correlates with values reported in the literature. Carvalho and Nahuz (2001) reported 17.1 μm ; Rao et al. (2002) reported 14.5 – 16.9 μm ; Quilhó et al. (2006) reported 20 μm ; Sharma et al. (2015) reported 14.3 – 16.8 μm . Across radial position, fibre diameter was higher in heartwood. The mean values for fibre diameter found by this study were not statistically different in either axial or radial directions.

The mean value of fibre double wall thickness (width) was 7.76 μm . The pattern for double wall thickness also decreased from the butt to the top, as with the fibre length. Radially, double wall thickness for fibres from sapwood were thicker than double wall thickness for fibres from heartwood. However, the reported mean values are comparable to those reported by Sharma et al. (2015) for 6-year-old *Eucalyptus* hybrid trees. The fibre double wall thickness exhibited mean values that were not statistically different.

This study revealed that fibre length and double wall thickness were comparatively higher in sapwood than in heartwood. This observation suggests that sapwood could be denser than heartwood in young wood. Similar observations have been reported in literature for both young and older *Eucalyptus* species; 6.5-year-old trees (Pillai et al. 2013), 10-year-old trees (Tomazello 1987), 15-year-old trees (Carrillo et al. 2015), 18-year-old trees (Trevisan et al. 2013) and 37-year-old trees (Melo et al. 2018). The authors attributed their observation to cambial age as particularly related *Eucalyptus* species.

3.3 Tissue proportion

Fibre carried a proportion of 37.54% and vessel elements carried 18.60%. Axial and radial parenchyma proportion were about 22% and 21% respectively (Table 3). Axial and radial variation in tissue proportion was recorded within trees. Study findings are compatible with studies on similar *Eucalyptus* hybrid species (Hu et al. 2008) and a 4.5-year-old

Eucalyptus tereticornis (Rao et al. 2002). However, the differences reported in the present study were statistically insignificant. Generally, the radial variation, though insignificant, was a little pronounced, but only at the butt section for the tissue proportional traits. Practically, the findings suggest that the studied wood materials may be utilized irrespective of its portion on the stem. Meanwhile, the service life of the young wood could be compromised as described in Brischke et al. (2006); a direct decay-influencing factor, among others, is a material natural resistance.

3.4 Vessel characteristics

Generally, vessels were exclusively solitary with a diffuse porous arrangement. Vessel characteristics affect the papermaking properties of wood and other technologies like impregnability (Amidon 1981, Barauna et al. 2014, Anupam et al. 2016). The mean values for vessel area, based on cross sectional view, for the 4-year-old *Eucalyptus* hybrid wood is 9462 μm^2 (Table 4). Vessel area was larger in sapwood than in heartwood. Same variable increased from the butt to the middle portion of the tree before a slight decrease at the top portion. Regarding vessel quantity, the estimated mean value was approximately 14 per mm^2 . The top portions had highest vessel frequency followed by the butt before the middle portion. Statistically, the effect of axial and radial position on vessel quantity and size was highly significant. Practically, the results suggest that positions are important when considering the young wood for application. For instance, in cases where impregnation of preservatives is required, different portions of the stem would give different outputs.

Table 3. Mean tissue element proportion (%), based on cross section area, for 4-year-old *Eucalyptus* hybrid (*E. grandis* x *E. urophylla*) grown in Ghana.

Variable	Position	Heartwood	Sapwood	P-value
Fibre (%)	Top	–	35.13 (8.31)	0.60910
	Middle	38.67 (9.00)	38.33 (10.47)	
	Butt	37.00 (12.07)	41.00 (8.97)	
Overall mean		37.54 (2.34)		
Vessel (%)	Top	–	20.43 (5.50)	0.32011
	Middle	18.00 (6.90)	17.33 (7.76)	
	Butt	19.67 (6.94)	15.75 (5.68)	
Overall mean		18.60 (1.90)		
Axial parenchyma (%)	Top	–	23.40 (7.35)	0.2456
	Middle	21.00 (7.59)	22.33 (6.51)	
	Butt	21.67 (7.24)	23.25 (7.30)	
Overall mean		22.51 (1.43)		
Radial parenchyma (%)	Top	–	21.05 (7.27)	0.8270
	Middle	22.33 (6.66)	22.00 (8.82)	
	Butt	21.67 (11.75)	20.50 (8.72)	
Overall mean		21.43(0.77)		

The P-values for each variable are from a two-way ANOVA run at 95% confidence interval. In parenthesis are the standard deviation of the mean values. – is used because the top portion had not developed heartwood yet. Total sampled trees (n) = 6.

Tukey's Honest Significant Difference was employed to test where the significant difference existed among the axial positions. Regarding vessel area, the butt portion

contributed greatly compared to the middle and the top. Conversely, for vessel frequency, the top portion contributes greatly when compared to both butt and middle. The pattern of vessel characteristics in this study conforms to earlier reports ((Taylor 1973, McKimm – Ilic 1987, Leal et al. 2003). The axial and radial variations observed in this study for vessel characteristics can be attributed to cambial age as related to eucalyptus species, and reported in literature (Leal et al. 2003, Ramírez et al. 2009, Carrillo et al. 2015).

Table 4. Mean vessel frequency per mm² and area (μm²) for 4-year-old *Eucalyptus* hybrid (*E. grandis* x *E. urophylla*) grown in Ghana. (VA): Vessel Area; (VF): Vessel Frequency.

Variable	Axial position	Heartwood	Sapwood	P-value
VA (μm ²)	Top	–	9503.73 (3573.25)	1.188e–05
	Middle	7816.69 (3993.39)	13544.41 (5955.02)	
	Butt	6321.15 (2729.22)	9982.50 (5037.37)	
Overall mean		9462.04 (2717.98)		
VF/mm ²	Top	–	17.70 (1.93)	1.371e–06
	Middle	15.00 (2.36)	6.60 (1.51)	
	Butt	15.50 (2.12)	11.40 (1.65)	
Overall mean		13.98(4.31)		

The P-values for each variable are from two-way ANOVA run at 95% confidence interval. In parenthesis are the standard deviations of the mean values. – is used because the top portion had not developed heartwood yet. Total sampled trees (n) = 6.

4 CONCLUSIONS

This study contributes to addressing the scarce scientific literature on eucalyptus in Africa. The focus on selected anatomical properties and morphological features is an important start for the resilient species. The height, diameters, and other morphological traits identified for the 4-year-old eucalyptus hybrid wood suggest that the hybrid species could qualify for numerous applications and further related tests. The axial and radial positions within the trees had no significant effect on fibre dimensions and tissue proportions. On the contrary, axial and radial positions had significant effect on vessel frequency and area. Meanwhile, the mean values found for all variables agreed with reported values of eucalyptus species grown through seed and clones in both native and cultivated lands. Comparatively, vessels were larger in area, but fewer by frequency in sapwood than in heartwood. Additionally, both vessel area and frequency increased from butt to top portion. The findings of this study highlight some of the fundamental information needed to support efficient utilization of eucalyptus wood, especially in Ghana. In this regard, it would be helpful to conduct further research to establish the effect of age, planting distances, etc., on wood properties of the *Eucalyptus* hybrid species in Ghana.

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Guide for Authors

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Contents and Abstracts of the Bulletin of Forest Science

Bulletin of Forest Science (Erdészettudományi Közlemények) is a journal supported by the Forest Research Institute of the Faculty of Forestry of the University of Sopron. The papers are in Hungarian, with English summaries. The recent issue (Vol. 11, 2021) contains the following papers. The full papers can be found and downloaded in *pdf* format from the journal's webpage (www.erdtudkoz.hu).

Vol. 11, Nr. 1, 2021

Katalin RUSVAI and Szilárd CZÓBEL:

Weed invasion of bait sites in the Mátra landscape Protection Area

Abstract - Our aim was to assess the effects of feeding places for hunting wild boar (bait sites). We selected 3-3 sites, located in forest, clearing area and on road. 4 transects were arranged from the centre of the sites, each consisting of 22 1 m² quadrats, where vegetation surveys were carried out in several years and periods. For the seed bank experiment, soil samples were taken at the centre of each bait and control sites. Then, seedling emergence method was used. We also measured soil P, K and NO₃⁻. Bait sites in clearings were the most invaded, possibly due to greater accessibility. Forest baits were the least weedy, road baits' degradation depends on their exposure and usage. The proportion of weeds was always higher in August, at clearings T4 weeds dominated. We detected a stress gradient: weeds were dominant in the centre, but with the distance they decreased, while natural species increased. At baits, the proportion of weeds in the seed bank was larger than in the control. Soil P, K and NO₃⁻ was also higher in the centre of baits. Besides degrading the vegetation, baits have negative effects on seed bank and soil as well, so they could be the focal points of biological invasions

<https://doi.org/10.17164/EK.2021.001>

Arnold ERDÉLYI, Judit HARDTDÉGEN, Ákos MALATINSZKY, Csaba János LESTYÁN and Csaba VADÁSZ:

Impacts of different silvicultural practices on the spread of tree of heaven (*Ailanthus altissima* (Mill.) Swingle) in calcareous sand forests

Abstract - We examined the changes in the prevalence and abundance of Tree of Heaven in several forest stands in the Peszérierdő (Central Hungary), where logging activities were carried out or previously stump deposits were made. According to our results, selective thinning and clear-cutting can have a significant effect on the activation of the seed bank of Tree of Heaven. Due to the abrupt growth of light availability, the soil disturbance and the other effects of log transport, the forest management activities may result in a reforestation, where the Tree of Heaven becomes dominant. In comparison to the spontaneous spread measured in control stands, forest management activities resulted even in a hundred times higher growth in both the prevalences and abundances of Tree of Heaven from one year to

another. In the surveyed artificial reforestations, the stump deposits proved to be the main objects where this species can regenerate from. It can resprout from its stumps and root remnants as well, then propagate within a few years and invade the intact, young stands. In addition – based on our local observations –, we also highlight the verticillium wilt as a control possibility against the Tree of Heaven.

<https://doi.org/10.17164/EK.2021.002>

Csenge Veronika HORVÁTH, Flóra TINYA, Bence KOVÁCS and Péter ÓDOR:

The effect of different forestry treatments on the understory vegetation of a sessile oak-hornbeam forest

Abstract - In the framework of a multitaxon forest ecological experiment, we compared the effects of different treatments of rotation and selection silvicultural systems on the understory vegetation of a sessile oak-hornbeam forest stand. The five treatments were: clear-cutting, keeping a retention tree group in the clear-cut, preparation cutting, gap-cutting, and closed mature stands were used as control. We compared species richness, total cover and composition of the understory vegetation, and cover of four plant functional groups in the second and fourth year after the interventions across the treatments. Species richness and total cover increased the most until the fourth year in clear-cuts and gaps, moderately in preparation cuts and the least in retention tree groups. Species composition changed the most in clear-cuts: here the cover of non-forest herbs increased, while species typical of woodlands could prevail in gaps. Gaps and preparation cuts provided the most favourable conditions for forest herbs and for the cover increase of woody saplings, supporting that harvesting methods sustaining continuous forest cover could possibly integrate both conservation and timber production aims.

<https://doi.org/10.17164/EK.2021.003>

László BALI, Dániel ANDRÉSI, Katalin TUBA and Csaba SZINETÁR:

Ground-dwelling spider fauna of the Nyíri-forest near Kecskemét, Hungary

Abstract – During our survey, we investigated the ground-dwelling spider fauna of five forest sub-compartments (32-117 years old; with species as grey poplar, pedunculate oak and black locust) belonging to the Nyíri-forest of Central Hungary, using pitfall traps. Sampling was conducted during the year of 2016, through 190 days. We collected 1802 specimen of 39 spider species. *Pardosa alacris* was the most common species, with 361 specimen. Gnaphosidae was the most species rich spider family, with 8 species. Most of the trapped spiders were cursorial hunters. The community showed the highest activity during June. According to the indicator species, the surveyed forest can be considered open and relatively dry, and in a good condition regarding its naturalness. The values of the Shannon diversity indices and the equitability were generally low. According to the ordination analysis, the samples collected from different forest sub-compartments separated from each other noticeably.

<https://doi.org/10.17164/EK.2021.004>

Balázs Gábor BALÁZS, Katalin TUBA and Ferenc LAKATOS:

The role of microorganisms in the ecology of bark beetles (Curculionidae, Scolytinae)

Abstract – Some bark beetle species (Curculionidae, Scolytinae), especially in coniferous forests, are major factors for mass mortality of trees. Although bark beetle species usually do not attack healthy trees, they can colonize weakened or dying trees. Some species may have massive outbreaks, especially under defined abiotic conditions (like hot and dry weather or

after wind and snow damage) and can have significant economic and ecological effect. Microorganisms associated with bark beetles such as fungi or bacteria play important roles in their colonization success, development, and gradation. This paper provides a review on the effects of microorganisms on the biology of bark beetles and interactions between bark beetles and their host plants. We present these interactions based on the holobiont theory, i.e., considering bark beetles and their associated microbiota as a whole.

<https://doi.org/10.17164/EK.2021.005>

Vol. 11, Nr. 2, 2021

Tamás KOLLÁR and Attila BOROVICS:

The updated methodological directives of data processing and maintainance of the Hungarian long term forestry experimental network, and its most important results

Abstract – The Hungarian long-term forestry experiment network was established in 1962, with the lead of Rezső Solymos, The Forest Research Institute has been running the network continuously since that time and its data are under research. The basic objectives of the network are unaltered since the establishment. The primary aim was to create a suitable basis for silvicultural and forest yield research in Hungary. The experiment plots take place in forest stands of common beech (*Fagus sylvatica*), sessile oak (*Quercus petraea*), Turkey oak (*Quercus cerris*), pedunculated oak (*Quercus robur*), hornbeam (*Carpinus betulus*), common ash (*Fraxinus excelsior*), Scots pine (*Pinus sylvestris*), black pine (*Pinus nigra*) and Norway spruce (*Picea abies*). More than 3000 plots, about 11000 survey reports (diameter, height, classification) are available, from which more than 6600 survey reports are digitally accessible. About 1200 plots are still monitored. The detailed methods of alignment, measurement and maintenance of the experimental plots and the most important publications of the long-term experiments are summarized. From these, the national forest yield tables and silvicultural treatment models are significant, but with the possession of new data, reformation is necessary.

<https://doi.org/10.17164/EK.2021.006>

Ferenc SZMORAD, Kristóf KELEMEN, Kata KENDERES and Tibor STANDOVÁR:

Assessment of composition, structure and dead wood supply in forests of the North Hungarian Mountains, Hungary

Abstract – The main objective of our project entitled „Multi-purpose assessment serving biodiversity conservation in the Carpathians region of Hungary”, supported by the Swiss-Hungarian Cooperation Program, was to develop a new forest state description methodology and to apply it to survey nearly 50,000 hectares of forests in three regions (Börzsöny, Mátra, Aggtelek Karst) of the North Hungarian Mountains. The present study evaluates the composition and structure of tree canopy and deadwood supply based on data collected by systematic sampling, fine spatial resolution and by recording numerous variables. The results show the compositional and structural richness of the Aggtelek karst, the lack of admixing tree species and a better supply of standing dead wood in the Mátra, the higher variation in canopy closure in the Börzsöny. There is no significant difference between the regions in terms of lying dead wood, and invasive trees species (black locust, tree of heaven). Among the practical conclusions, the dependence of certain characteristics (admixing trees, dead wood) on management is emphasised, and related management proposals are made.

<https://doi.org/10.17164/EK.2021.007>

Tamás Márton NÉMETH, Orsolya SZABÓ and Norbert MÓRICZ:

Comparative drought sensitivity analysis of young oak stands in Somogy County (Hungary)

Abstract – This paper analyses the drought induced growth responses of oak stands, Sessile oak (*Quercus petraea*) and Turkey oak (*Q. cerris*), along a precipitation gradient in Somogy County. 136 tree-ring samples were analysed and dendroecological metrics were also applied to assess the drought sensitivity of the species. Water deficit was estimated by using the soil water budget based water stress index. Results indicated a strong dependency of annual tree ring width on the water availability of current year summer but found different strategies of the two tree species against drought conditions. Turkey oak responded more sensitively to droughts than sessile oak revealed by the significantly lower resistance and higher recovery potential of this species. A linearly proportional increase of growth reduction with rising water stress was found for Turkey oak while the growth response of sessile oak decreased considerably with increasing aridity indicating lower growth plasticity of sessile oak to droughts there. Based on our findings it seems that Turkey oak copes better with droughts than sessile oak and may gain competitive advantages under the projected climate change.

<https://doi.org/10.17164/EK.2021.008>

Tamás MOLNÁR, Zoltán SOMOGYI and Géza KIRÁLY:

Forest monitoring plan of Farkas-erdő of Sárvár based on Sentinel-2 satellite images and cloud computing

Abstract – The satellite based remote sensing forest monitoring system of Farkas-erdő of Sárvár was created to utilize high resolution ESA Sentinel-2 images and cloud computing, where processing, analysing, and displaying of health state changes of forests takes place online, in the Google Earth Engine. The system aims to monitor the forest health state change constantly with high precision in the investigation period of 2017-2020, using maps and graphs made of vegetation and moisture indices. Remotely sensed data was compared to field-based damage reports for validation purposes.

<https://doi.org/10.17164/EK.2021.009>

